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User's Manual for Axisymmetric Diffuser Duct (ADD) Code

Volume II—Detailed ADD Code Description

O. L. Anderson, G. B. Hankins, Jr.,
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USER'S MANUAL FOR
AXISYMMETRIC DIFFUSER DUCT
(ADD) CODE

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VOL. II DETAILED ADD CODE DESCRIPTION

5.0 GLOBAL STRUCTURE OF ADD CODE

This section of the manual is intended for the special user who wishes to modify the ADD code or adopt the ADD code to a diffferent computer. Section 5.0 provides an overview of the code in terms of the principal tasks. These principal tasks are clearly labeled in the main program ALTMN and agree with the tasks listed in the Global Task Chart Section 5.2 and the Global Tree Structure Section 5.3. Internal flags, as opposed to input options, are described in Section 5.4. These flags are set by the code and control the calculation flow between different subroutines. Flags used only within a subroutine are described in the detailed subroutine descriptions in Section 7.0.

Special problems associated with machine specific language are also described in this Section. The operation of a general I/O routine, which uses UNIVAC library I/O routine NTRAN, and a description of the data files is given in Section 5.5. This general I/O routine has been developed to allow NTRAN compatibility with ANSI standard DEFINE FILE for easy conversion. The ADD code also uses a standard spline smoothing routine ICSVKU provided by International Mathematical and Statistical Libraries, Inc. The use of this subroutine is described in Section 5.6. All labeled CØMMØN block and DIMENSIØN statements are set by INCLUDE statements. Block sizes and EQUIVALENCE statements are set by PARAMETER statements. The use of these in the code is described in Section 5.7.

5.1 Main Program ALTMN

Object

Main program for ADD code

Options

See Input Options Section 4.2

Variables

See CØMMØN BLØCKS in Sect. 6.1.

Theory

The main program executes the major tasks according to the input options IØPT as shown by the global task chart described in Section 5.2.

5.2 Global Task Chart

The major tasks are called in sequence by the main program ALTMN which is the only purpose of the main program. These tasks are executed, according to the input options, by calling only the subroutine listed on the Global Task Chart. The major tasks are labeled on the Task Chart as they are labeled by comment cards in the main program. Each major task may be executed independently and therefore may be overlayed. However, since it is not necessary to overlay every task, more than one subroutine (task) may be in the same UNIVAC MAP segment of the overlay. The UNIVAC MAP segment is given in the brackets following the calling subroutine listed on the Global Task Chart.

5.2 Global Task Chart

No.	Task	Subroutine (segment)
0.0	Print Title Page	ØUTPUT (INITO)
1.0	Read Input Variables	REDINP (RØØTM)
1.1	Print Input Variables	ECOINP (INITO)
2.0	Set Up Problem	
2.1	Calculate Duct Geometry	GDUCT (INIT)
2.2	Normalize Geometric Variables	FNØRM (INITO) SLØTA (CØRE)
2.3	Calculate, Store, Read Coordinates	CØØRST (CØRE)
2.4	Set Up Blade Geometry	BLDGØM (FØRCESEG)
2.5	Construct Slots in Duct	SLOTA (CØRE)
2.6	Check Inlet Flow Conditions	CKINPT (INIT1)
2.7	Calculate Inlet Flow Conditions	WFITER (INITO)
2.8	Normalize Flow Variables	FNØRM (INITO)
3.0	Print Flow Set Up Conditions	
3.1	Print Default Input Parameters	WRTINP (RØØTM)
3.2	Print Calculated Coordinates	WRTGDC (RØØTM)
4.0	Calculate Inviscid Flow Field	
4.1	Calculate Potential Flow Field	PØISØN (PSI)
4.2	Calculate Rotational Flow Field	CALINV (INIT1)
5.0	Calculate Blade Forces	FORCE (FØRCESEG)
6.0	Calculate Wall Bleed	WBLEED (INIT1)

5.2 GLOBAL TASK CHART (Cont'd)

No.	Task	Subroutine (segment)
7.0	Calculate Viscous Flow Field	SØLVI (CØMP)
8.0	Print Output Summary	
8.1	Print Neglected Terms	PRTØUT (NGADD)
8.2	Print Slot Flow Conditions	SLØTA (CØRE)
8.3	Print Mean Flow Summary	WRTSUM (WRTP)
8.4	Print Calculated Blade Forces	FØRCE (FØRCESEG)
8.5	Print Boundary Layer Parameters	BLPARM (ENDIN)
8.6	Print Solution on Output Line	FØUTP (SØUTP)

5.3 Global Tree Structure By Task

An overall view of the ADD code is shown in the Global Tree Structure shown on the following pages. This tree structure is arranged by tasks and labeled as they appear in the main program ALTMN. Column 1 shows the main program which calls the subroutines in column 2. Each subroutine in column 2 executes a major task and calls the subroutines in column 3. For any given calculation not all branches of the tree are called. As an example, if the coordinates have been calculated and stored on a data file (IØPT9=3), then CØØRST (Task 2.3) is not executed. CØØR is a general subroutine which reads and interpolates the data on the coordinate file and BLKRED is a general subroutine for reading data blocks. Thus these two subroutines are used throughout the code. Subroutine CØØR can also call CØØR1 which is an approximate coordinate calculation used when IØPT9=0. The user who wishes to replace the UNIVAC general I/O routine NTRAN with standard ANSI FORTRAN DEFINE FILE need only modify subroutine BLKRED. The IMSL routines are only called by subroutine SMØØTH and the user may replace the IMSL routines by only modifying this routine.

5.3 Global Tree Structure By Task

0.0	Print Title Page			
ALTMN	OUTPUT			
1.0	Read Input Variables			
ALTMN	REDINP ECØINP	SLØTA		
2.0	Set Up Problem 2.1 Calculate Duct Geometry			
ALTMN	GDUCT	SMØØTH INITQ BLKRED	ICSYKU BLKRED	ICSFKY ICSFKU UERTST
	2.2 Normalize Geometric Variables			
ALTMN	FNØRM SLØTA	TRBLDE AMU		
	2.3 Calculate, Store, Read Coordinates			
ALTMN	CØØRST	TPRINT CØØR1 CØØR4 CØØR2 CØØR3	 XT XH CDS RØBRTS DRØBRT GBLADE SMØØTH CPLX1 FINTG CPLX1 FETA FINTG GBLADE CØØR5	 FTHIK ICSVKU FCPLX FCPLX FTHIK

2.4 Set Up Blade Geometry				
ALTMN	BLDGØM	TRBLDE	ALINE	RDCØR
		FLINE	CROSS1	
			BLINE	
			CLINE	
			DLINE	
			CRØSS2	CRØSS1
			ELINE	
		SLETE	TRLETE	
			TRBLDE	
			ALINE	RDCØR
2.5 Construct Slots In Duct				
ALTMN	SLØTA			
2.6 Check Inlet Flow Conditions				
ALTMN	CKINPT	TPRINT		
		CØØR	CØØR1	XT
				XH
				CDS
				RØBRTS
				DRØBRT
				GBLADE
			BLKRED	
			GBLADE	FTHIK
		WRTCKI		
2.7 Calculate Inlet Flow Conditions				
ALTMN	WFITER	CØØR	BLKRED	
			GBLADE	FTHIK
			CØØR1	XT
				XH
				CDS
				RØBRTS
				DRØBRT
				GBLADE
		FLØWIN	UBLAS	
			AMU	
			CFCØLE	
			BPLUSR	
			FCØLES	BPLUSR
			AMF	
			ERPIN	

5.3 Global Tree Structure By Task (Cont'd)

2.8 Normalize Flow Variables				
ALTMN	FNØRM	TRBLDE AMU		
3.0 Print Flow Set Up Conditions 3.1 Print Input Parameters				
ALTMN	WRTINP			
3.2 Print Calculated Coordinates				
ALTMN	WRTGDC	CØØR	BLKRED GBLADE CØØR1	 FTHIK XT XH CDS RØBRTS DRØBRT GBLADE
4.0 Calculate Inviscid Flow Field 4.1 Calculate Potential Flow Field				
ALTMN	PØISØN	TPRINT INITQ INTFRE PØISCF PØIS SCURVA	 BLKRED TPRINT BLKRED FETA BLKWRT READPF WRITPF READPG BLKRED BLKWRT QINTER	 BLKRED BLKWRT BLKRED BLKRED BLKWRT

4.2 Calculate Rotational Flow Field				
ALTMN	CALINV	TPRINT		
		CØØR	BLKRED	FTHIK
			GBLADE	XT
			CØØR1	XH
				CDS
				RØBRTS
				DRØBRT
				GBLADE
		BLKWRT		
		WRTCAL		
5.0 Calculate Blade Force				
ALTMN	FØRCE	TPRINT		
		CØØR	BLKRED	
			GBLADE	FTHIK
		GBLADE	FTHIK	
		BLKRED		
		FINVIS		
		CASC		
		BLKWRT		
6.0 Calculate Wall Bleed				
ALTMN	WBLEED	BLKRED		
		WRTBLD		
7.0 Calculate Viscous Flow Field				
ALTMN	SØLVI	TPRINT		
		BLKRED		
		CØØR	BLKRED	
			GBLADE	
		FØRCL	GBLADE	
		ØRTFUN		
		SLTFLØ	AMU	
			CFCØLE	
			FCØLES	BPLUSR
		STRESI	TURB	AMU
		TURB	AMU	
		MINVRT		
		BLKWRT		
		FCØRCT		
		TURB2Q	AMU	
			SUBLAY	
		FAVER		
		WRTSØV	AMU	
			BAMFØR	

8.0 Print Output Summary 8.1 Print Neglected Terms				
ALTMN	PRTØUT	BLKRED		
		CØØR	BLKRED	
			GBLADE	
			CØØR1	XT
				XH
				CDS
				RØBRTS
				DRØBRT
				GBLADE
		VARFUN		
8.2 Print Slot Flow Conditions				
ALTMN	SLØTA			
8.3 Print Mean Flow Summary				
ALTMN	WRTSUM	BLKRED		
		QPTMAX		
8.4 Print Calculated Blade Force				
ALTMN	FØRCE	GBLADE	FTHIK	
		BLKRED		
		CØØR	BLKRED	
			GBLADE	FTHIK
			CØØR	XT
				XH
				CDS
				RØBRTS
				DRØBRT
				GBLADE
8.5 Print Boundary Layer Parameters				
ALTMN	BLPARM	BLKRED		
		AMU		
		CØØR	BLKRED	
			GBLADE	XH
			CØØR1	XT
				CDS
				RØBRTS
				DRØBRT
				GBLADE

5.3 Global Tree Structure By Task (Cont'd)

8.6 Print Solution on Output Line				
ALTMN	FOUTP	INITFV		
		TPRINT		
		ALINE	BLINE	
			CRØSS1	
		BLINE		
		FLINE	ALINE	BLINE
				CRØSS1
			RDCØR	BLKRED
			BLINE	
			CLINE	
			DLINE	
			CRØSS2	
			ELINE	
		RECØRD		
		CØØR	BLKRED	
			GBLADE	FTHIK
		BLKRED		
		WRTFØU		

5.4 List of Internal Flags

Flag Name		Function
NØPT1	= 0	Set up initial flow
	= 1	Calculate flow station J
NØPT2	= 1	Adiabatic wall
	= 2	Prescribed wall temperature
NØPT3	= 1	Calculate and store approximate coordinates
	= 2	Calculate local approximate coordinates
NØPT4	= 1	Duct with centerbody
	= 2	Duct without centerbody
NØPT5	= 0	Continue calculation
	> 0	Fatal error - stop calculation
NØPT6		Force backpressure iteration counter
NØPT7		Block I/O counter in CALINV
NØPT8		Block I/O counter in SØLVI
NØPT9	= 0	Complete complex function calculation
	= 1	Shortened complex function calculation
NØPT10		Not used
NØPT11		Not used
NØPT12		Not used
NØPT13		FCPLX Flag
NOPT14		Not used
NOPT15	= 0	Integrate along S
	= 1	Integrate along n
NØPT16		SØLVI station counter
NØPT17		Not used
NØPT18	= 0	Turbulent flow
	= 1	Laminar flow
NØPT19		Weight flow iteration counter
NØPT20	= 0	Optimize step size KDS
	= 1	Fixed KDS
NØPT21	= 0	Greater than critical Reynolds number
	= 1	Less than critical Reynolds number
NØPT22		Not used

5.5 General Input/Output for Data Files

The file assignments are described in Table I. This table shows the unit number, the names of the arrays stored on the file, the block (record) length in words, the number of blocks (records), and the subroutine generating the file. All unit numbers are set by parameter statements (in brackets). Thus, changing the unit numbers requires changing only the paramater statements. All arrays are single precision except AAF or unit LDRUM which is double precision. The data stored on unit JDRUM and unit KPØIS are similiar. Unit JDRUM has coordinate data for a non-uniform mesh used by subroutine SØLVI to obtain the solution of the viscous flow field. Unit KPØIS has the coordinate data for a uniform mesh used by subroutine PØIS to obtain the compressible axisymmetric potential flow solution. The number of blocks (records) stored on the files is set primarily by the number of streamwise coordinate stations calculated by subroutine CØØRST. The maximum numbers of streamwise stations (IS) is set by a parameter statement such that JL $\leq$ IS. The number of words in a block (record) is set primarily by the number of streamlines KL calculated by subroutine CØØRST. The maximum number of streamlines IST is set by a parameter statement such that KL $\leq$ IST. Subroutine PØIS has provision for read/write of NST blocks (records) where NST is set by a parameter statement.

All data files are read/written by a general I/O routine BLKRED, with a second entry point BLKWRT, which uses a UNIVAC Library I/O routine NTRAN. This subroutine, BLKRED, has been specially developed to allow NTRAN compatability with ANSI standard FØRTRAN DEFINE FILE. Thus, the user who wishes to use DEFINE FILE need change only one subroutine, BLKRED, which is described in detail in Section 7. In addition to the general routine BLKRED, special I/O routines have been developed which still use BLKRED. Subroutine CØØR reads two successive blocks of coordinate data and interpolates to obtain the fine grid used by subroutine SØLVI when KDS > 1. Subroutines READPF, READPG, WRITPF, which also use BLKRED, is specially developed to read NST blocks (records). The logic for counting blocks (records) is built into these subroutines and described in Section 7.

When using the global iteration option IØPT14 > 0 or for post processing of data such as drawing CALCØMP plots, the corresponding record numbers for the inviscid solution stored on file MDRUM, the viscous solution stored on file NDRUM, and the coordinate data stored on file JDRUM must be obtained. This is shown in Table II. The parameters controlling the record counting are shown on the top of the table. The mesh size parameters JLXKL is stored on the coordinate file along with scale factors. The remaining parameters controlling the record counting are stored on the <u>first</u> record on file NDRUM. For IØPT14 = 0, the viscous solution is stored only for each Jth coordinate station regardless of the value of KDS used in the calculation. Therefore, set KDS = JKDS = 1. For IØPT14 > 0, the viscous solution is stored for every interpolated station on the fine grid (JKDS = 1, KDS). Therefore, to recall data at a Jth coordinate station set JKDS = 1 and KDS equal to the value used in viscous flow calculation. In some cases the solution stops before completion. NØPT7 and NØPT8 are the number of records stored on files MDRUM and NDRUM respectively. Therefore,

$$NØPT7 \leq IØPT16 - IØPT15 - 1$$

$$NØPT8 \leq KDS\ (IØPT16 - IØPT15) + KDS - 1$$

Table I

Table of File Assignments

UNIT NO.	ARRAY NAME	BLOCK LENGTH (WDS)	NO. BLOCKS	SUBROUTINE WRITING BLOCK
*8(NDRUM)	F(NEQ,3,IST) FPARM(15)	3915	JL-2	SØLVI
9(JDRUM)	JSTEP Q(19,IST) RHS(10) RMS(10) RTS(10) DSTEP QPARM(9)	2514	JL	CØØRST
10(CDRUM)	FF(17,2,IST)	4420	1	FØRCE
11(LDRUM)	AFF(LNGT0)**	6600	5	SØLVI
12(LFØRC)	FØRC	780	1	FØRCE
19(KPØIS)	JSTEP Q(19,IST) RHS(10) RMS(10) RTS(10) DSTEP QPARM(9)	2514	JL	CØØRST
22(MDRUM)	FIV(NEQ,3,IST) FIPARM(15)	3915	JL-2	CALINV
23(NFDRM)	F(IST4)	134	JL+NST-2	PØISCF
24(NPDRM)	P(IST)	130	JL+NST-2	PØIS
25(NGDRM)	BLK(NGIST)	400	JL+NST-2	PØISCF

* KDS*JL-2 blocks when IOPT14 > 0, JL $\leq$ IS

**Double precision variables

IS = 100

NST = 25

Table II

Table of Record Counting

JL	= QPARM(3)	, No. streamwise coordinate, JL $\leq$ IS
KL	= QPARM(4)	, No. streamline coordinate, KL $\leq$ IST
*KDS	= FPARM(10)	, No. steps/station fine grid
NØPT7	= FPARM(12)	, No. MDRUM records
NØPT8	= FPARM(13)	, No. NDRUM records
IØPT15	= FPARM(14)	, First J station
IØPT16	= FPARM(15)	, Last J station
J		, Record no. for coordinates, J = 1, JL
JRECFI		, Record no. for inviscid solution
JRECFV		, Record no. for viscous solution
**JKDS		, Fine grid station counter, JKDS = 1, KDS

FIV(I,N,K) Array

JRECFI = J-IØPT15-1	, N = 3, for J > IØPT15 + 1
JRECFI = 1	, N = 2, for J = IØPT15 + 1
JRECFI = 1	, N = 1, for J = IØPT15

F(I,N,K) Array

JRECFV = KDS*(J-IOPT15)+JKDS-1	, N = 3, J > IØPT15
JRECFV = 1	, N = 2, J = IØPT15

* KDS = 1 for IØPT14 = 0
**JKDS - 1 for Jth record

5.6 IMSL Routines

The ADD code uses a standard least squares cubic spline routine provided by International Mathematical and Statistical Libraries, Inc. This routine is called ICSVKU and is described in the IMSL library dated November 1975. Subroutine ICSVKU computes a least squares approximation to a given set of points by a cubic spline with a given number of knots. Since the successful use of splines for purposes of providing a smooth approximation to a given set of points depends strongly on the proper placement of the knots, ICSVKU starts with a given set of knots and varies them one by one in order to determine the knot locations that minimizes the least square error. Subroutine ICSVKU also uses subroutines ICSFKU, ICSFKV and VERTST.

The least square spline routine ICSVKU is called by only subroutine SMØØTH which is described in Section 7. Subroutine SMØØTH, however, uses ICSVKU to spline fit the second derivative of the data points. Therefore, for the user who does not have the IMSL library or wishes to replace ICSVU, a brief description of the subroutine is given on the following page.

Subroutine ICSVKU (Arg. List)

Object

Calculate least squares spline fit

Options

None

Arg. List

X(I)	X_I	, Vector containing NX abscissa points
F(I)	F_I	, Vector containing NX ordinate points
NX	N	, Number of elements in X and F
XK(K)	$\tilde{X}_K$	, Vector containing NXK knot locations
NXK	M	, Number of knots
Y(K)	Y_K	, Vector of NXK-1 spline coefficients
C(K,3)	C_{KL}	, Matrix of NXK-1 x 3 spline coefficients
IC	NXK-1	, Dimension of spline coefficient row
ERRØR		, Cubic spline error
WK		, Work area of dimensions NS=(NXF+6)
IER		, Error parameter

Theory

The vectors (X_I, F_I, I = 1, NX) containing the points to be fitted with a cubic spline are input along with the vector ($\tilde{X}_K$, K = 1, NXK) which is the initial guess for the knot locations. The subroutine returns the spline coefficients (Y_K, $C_{K,L}$, L = 1, 3, k = 1, NXK-1) and the new locations of the knots ($\tilde{X}_K$, K = 1, NXK) where the spline coefficients are given in the form

$$\bar{F}(T) = ((C_{K3}+D + C_{K2}) + D + C_{K1}) + D + Y_K \qquad (1)$$

$$D = T-\tilde{X}_K \qquad (2)$$

where

$$\tilde{X}_K < T < \tilde{X}_{K+1} \qquad (3)$$

For this subroutine the end points are fixed and only the interior knots are moved. Subroutine SMØØTH treats Eq. (1) as an equation for the second derivative. Therefore, Eq. (1) is integrated analytically to obtain the smoothed curve with continuous fifth derivatives.

Reference

deBoor, Carl and John R. Rice: Cubic Spline Approximation II - Variable Knots. Computer Sciences Department TR21 Purdue University, April 1968.

6.0 GLOBAL VARIABLES

6.1 List of Labeled COMMON BLOCK Variables

Name	Object
ACØNS	Input blade geometry variables
ACØNSO	Blade geometry parameters
ADPS	Stored radial coordinate for slot interpolation
AINV	Variables for CALINV I/O
AKK	Complex coordinate flags
AMATRX	Variables for viscous flow matrix equations
AVER2	Variables for mass flow average calculation
BCPLX	Variables for complex coordinate calculation
BSLØT	Variable for slot geometry
BTHIK	Blade thickness variables
CCPLX	Variables for complex coordinate calculation
CINF	Parameters for Poisson equation
CØNST	Calculated gas properties
CØRE	Coordinate Functions
CØRE2	Calculated wall variables
CSLØT	Dimensionless slot geometry variables
DERIV	Strut force functions
DRED1	Coordinate variables I/O
DRED2	Coordinate variables I/O
DSKB	Parameters for I/O routine
DSLØT	Parameters for slot geometry
DUCØUT	Calculated wall coordinates

6.1 List of Labeled CØMMON BLØCK Variables (Cont'd)

DUCTIN	Input duct and flow data
FCØR	Mass Flow weighted flow errors
FIVC	Inviscid flow variables I/O
FLAGS	Internal flags
FLØWI	Initial flow variables
FØRS	Calculated blade force variables
FØRS2	Blade force variables
FUNC	Viscous flow variables
INTINP	Mesh parameters, input options, debug options
MATRXA	Variables for viscous flow matrix equations
NGTERM	Variables for neglected terms calculation
REALIN	Input flow properties, gas properties
SPECFD	Variables in Poisson equation
SPCGD	Variables for streamline curvature calculation
SPIØ	Initial flow variables, mass average variables
STRES	Geometric functions
STRMES	Poisson solver stretching parameters
SVARB	Mesh variables, flow variables
TITLIN	Title card
TRBL	Variables for two equation turbulence model
TURBS	Turbulent viscosity, conductivity
TURB2	Parameters for automatic step size algorithm

WLINE	Variables for locating arbitrary line
XFØU	Parameters for output data line calculation
ZFØU	Variables for output data line calculation

6.2 List of CØMMØN Block Variables

LIST OF VARIABLES IN CØMMØN/ACØNS/

Input Blade Geometry Variables

CØNSTI(1,L)	=	y'	, Independent variable (stacking line) (ft)
CØNSTI(2,L)	=	α_s	, Stagger angle from blade face (deg.)
CØNSTI(3,L)	=	c	, Blade chord (ft)
CØNSTI(4,L)	=	t/c	, Blade thickness/chord
CØNSTI(5,L)	=	ϕ_c	, Circular arc camber (deg.)
CØNSTI(6,L)	=	x'	, Dependent variable (ft)
ISHAPE			, Blade shape index
NB	=	N_B	, Number of blades
NUM	=	N	, Number of input points
ØMEGZI	=	Ω_Z	, Rotor speed (rpm)
RCLOI	=	r_{CLO}	, Radial location of stacking line (ft)
THCLI	=	θ_{CLO}	, Rotation of stacking line (deg.)
ZCLOI	=	z_{CLO}	, Axial location of stacking line (ft)
L	=	1,N	

LIST OF VARIABLES IN CØMMØN/ACØNSØ/

Blade Geometry Parameters*

CØNST(1,L)	=	y'/r_r ,	Independent variable
CØNST(2,L)	=	α_s ,	Stagger angle to axis (deg)
CØNST(3,L)	=	c/r_r ,	Chord
CØNST(4,L)	=	t/r_r ,	Blade maximum thickness
CØNST(5,L)	=	ϕ_c ,	Circular arc camber (deg)
CØNST(6,L)	=	x'/r_r ,	Dependent variable
CØNST(7,L)	=	x_{CL}/r_r ,	Streamline distance to center line (CL)
CØNST(8,L)	=	s ,	Streamwise coordinate of center line (CL)
CØNST(9,L)	=	n ,	Normal coordinate of center line (CL)
ALPHS	=	$\alpha_s(n)$,	Stagger angle to axis (deg)
ALPSH	=	α_{SH} ,	Stagger angle to axis hub (deg)
ALPST	=	α_{ST} ,	Stagger angle to axis tip (deg)
CHØRD	=	$c(n)/r_r$,	Chord
CHØRDH	=	c_H/r_r ,	Chord hub
CHØRDT	=	c_T/r_r ,	Chord tip
GAP	=	g/r_r ,	Gap
ØMEGZ	=	$\Omega r_r/u_r$,	Rotor speed
PHIC	=	ϕ_c ,	Circular arc camber angle (deg)
RCLH	=	r_{CLH}/r_r ,	Radius CL hub
RCLT	=	r_{CLT}/r_r ,	Radius CL tip
RCLØ	=	r_{CLO}/r_r ,	Radius to stacking line origin
RLEH	=	r_{LEH}/r_r ,	Radius leading edge hub
RLET	=	r_{LET}/r_r ,	Radius leading edge tip

SØLD	=	σ ,	Blade solidity
THCL	=	θ_{CL} ,	Rotation of stacking line, deg
THIKM	=	$t(n)/c(n)$,	Thickness/chord
THIKN	=	$t(n)/r_r$,	Blade maximum thickness
ZCLH	=	z_{CLH}/r_r ,	Axial location CL hub
ZCLT	=	z_{CLT}/r_r ,	Axial location CL tip
ZCLØ	=	z_{CLO}/r_r ,	Axial location stacking line origin
ZLEH	=	z_{LEH}/r_r ,	Axial location leading edge hub
ZLET	=	z_{LET}/r_r ,	Axial location leading edge tip

*See Subroutine GBLADE

LIST OF VARIABLES CØMMØN/ADPS/

Store Radial Coordinate for Slot Interpolation

DPSI(K)	=	$R'(K)$	,	Radial coordinate (dimensionless)
K	=	1,KL		

LIST OF VARIABLES IN CØMMØN/AKK/

Complex Coordinate Flags

M1	,	Flags for debug printout
M2	,	See subroutine FCPLX

LIST OF VARIABLES IN CØMMØN/AMATRX/

Variables for Viscous Flow Matrix Equations

AD(I,J)	=	d_{IJ} ,	Elements of D matrix (see SØLVI)
ADI(I,J)	=	d_{IJ}^{-1} ,	Elements of D^{-1} matrix (see SØLVI)

LIST OF VARIABLES IN CØMMØN/AINV/

Variables for CALINV I/O

CINP(1,K)	=	Π	,	Static pressure (P/P_r)
CINP(2,K)	=	Π_o	,	Total pressure (P_o/P_r)
CINP(3,K)	=	α	,	Swirl angle (deg)
CINP(4,K)	=	Θ_o	,	Total temperature (T_o/T_r)
K	=	1,KL		

LIST OF VARIABLES IN CØMMØN/AVERZ/

ASH	=	A_H	,	Surface area hub (dimensionless)
AST	=	A_T	,	Surface area tip (dimensionless)
DASH1	=	ΔA_H	,	Increment wall area hub (dimensionless)
DAST1	=	ΔA_T	,	Increment wall area tip (dimensionless)
DENTP1	=	ΔI	,	Increment in Entropy (dimensionless)
DPSI1	=	$\Delta \Psi$	,	Increment in mass flow (dimensionless)
DQSH1	=	ΔQ_H	,	Increment wall heat flux hub (dimensionless)
DQST1	=	ΔQ_T	,	Increment wall heat flux tip (dimensionless)
DTHEO1	=	$\Delta \Theta_o$	,	Increment in total temperature (dimensionless)
ENTP	=	I	,	Entropy (dimensionless)
ENTPO	=	I_o	,	Inlet entropy (dimensionless)
QSH	=	Q_H	,	Total heat flux hub (dimensionless)
QST	=	Q_T	,	Total heat flux tip (dimensionless)
THEO	=	Θ_o	,	Total temperature (dimensionless)
THEOO	=	Θ_{oo}	,	Inlet total temperature (dimensionless)

LIST OF SYMBOLS IN CØMMØN/BCPLX/

Variables for Complex Coordinate Calculation

A(1,I)	=	A_i	,	Source strength (dimensionless)
A(2,I)	=	b_i	,	Location of pole (dimensionless)
A(3,I)	=	α_i	,	Wall angle change (deg)
A(4,I)	=	r_i	,	Radius in z plane (dimensionless)
A(5,I)	=	ϕ_i	,	Angle in z plane (radians)
A(6,I)	=	$\bar{X}_i$	,	Relative X distance in z plane (dimensionless)
A(7,I)	=	$\bar{Y}_i$	,	Relative Y distance in z plane (dimensionless)
B(1,I,K)	=	ΔSX_s	,	Change in coordinate X (dimensionless)
B(2,J,K)	=	ΔSY_s	,	Change in coordinate Y (dimensionless)
B(3,I,K)	=	$\Delta S\xi_s$	,	Change in coordinate ξ (dimensionless)
B(4,I,K)	=	$\Delta S\eta_s$	,	Change in coordinate η (dimensionless)
X(1,K)	=	S	,	Streamwise coordinate (dimensionless)
X(2,K)	=	n	,	Normal coordinate (dimensionless)
X(3,K)	=	X	,	X coordinate in z plane (dimensionless)
X(4,K)	=	Y	,	Y coordinate in z plane (dimensionless)
X(5,K)	=	ξ	,	coordinate in w plane (dimensionless)
X(6,K)	=	η	,	coordinate in w plane (dimensionless)
X(7,K)	=	ξ_s	,	Streamwise derivative of ξ (dimensionless)
X(8,K)	=	η_s	,	Streamwise derivative of η (dimensionless)

LIST OF SYMBOLS IN CØMMØN/BCPLX/

X(9,K)	=	X(S+AS)	,	
X(10,K)	=	Y(S+AS)	,	
X(11,K)	=	ξ(S+AS)	,	Coordinates at Station S+AS
X(12,K)	=	η(S+AS)	,	
X(13,K)	=	V	,	Metric scale coefficients (dimensionless)
X(14,K)	=	ξ_{ss}	,	Second derivative of ξ (dimensionless)
X(15,K)	=	ξ_{sn}	,	Cross derivative of ξ (dimensionless)
X(16,K)	=	V_n	,	Normal derivative of V (dimensionless)
X(17,K)	=	V_s	,	Streamwise derivative of V (dimensionless)

LIST OF VARIABLES IN CØMMØN/BLSØT/

Variables for Slot Geometry

ALSLTI(N,L)	=	α_{SL}	,	Slot swirl angle (deg)
HSLØTI(N,L)	=	n_{SL}	,	Slot height (ft)
PØSLTI(N,L)	=	P_{OSL}	,	Slot total pressure (psfa)
TØSLTI(N,L)	=	T_{OSL}	,	Slot total temperature (deg R)
WØSLTI(N,L)	=	$\dot{W}_{OSL}$	,	Slot weight flow (lb/sec)
ZSLØTI(N,L)	=	Z_{SL}	,	Slot axial location (ft)

N=1 Tip wall

=2 Hub wall

L=1,15 Slot Number

VARIABLES IN CØMMØN/BTHIK/

KBLADE			,	Number of points
XK(I)	=	X_I	,	Fractional chordwise distance
YK(I)	=	Y_I	,	Thickness/Chord

I = 1, KBLADE

LIST OF VARIABLES IN CØMMØN/CCPLX/

Variables for Complex Coordinate Calculation

NPTS	=	N_p	,	Number of singularities in complex transformation
NSØURC	=	Ns	,	Number of sources in z plane
ØRDER1	=	O_1	,	Absolute magnitude of largest term
ØRDER2	=	O_2	,	Absolute magnitude of largest term
ØRDER3	=	O_3	,	Absolute magnitude of largest term
SLO	=	S_{LO}	,	Length of streamwise coordinate
XDS	=	dS	,	Step size for complex integration
XDN	=	dS	,	Step size for complex integration

LIST OF VARIABLES IN CØMMØN/CINF/

Parameters for Poisson Equation

AMINF	=	M_∞	,	Freestream Mach number
AN(K)	=	n_k	,	Transverse coordinate
DEDN(K)	=	$(d\eta/dn)_k$	,	Transverse coordinate stretching
D2EDN(K)	=	$(d^2\eta/dn^2)_k$	,	Transverse coordinate stretching
PINF	=	Π_∞	,	Freestream static pressure (dimensionless)
PSIKL	=	ψ_∞	,	Freestream stream function (dimensionless)
PTINF	=	Π_∞	,	Freestream total pressure (dimensionless)
RHØINF	=	ρ_∞	,	Freestream density (dimensionless)
RØTINF	=	$\rho_{o\infty}$	,	Freestream total density (dimensionless)
TEMINF	=	Θ_∞	,	Freestream static temperature (dimensionless)
TTINF	=	$\Theta_{o\infty}$	,	Freestream total temperature (dimensionless)
UINF	=	U_∞	,	Freestream velocity (dimensionless)
UPINF	=	$U_{\phi\infty}$	,	Freestream tangential velocity (dimensionless)
USINF	=	$U_{s\infty}$	,	Freestream streamwise velocity (dimensionless)
UUO	=	U_o	,	Reference velocity (dimensionless)
VVO	=	V_o	,	Reference metric coefficient

LIST OF VARIABLES IN CØMMØN/CØNST/

Gas Properties

ACHI	=	χ	,	Clauser constant (0.016)
AKAPPA	=	κ	,	von Karman constant (0.41)
APLUS	=	A^+	,	van Driest constant (26.0)
CPR	=	C_p	,	Specific heat at constant pressure (5997.0 ft^2/sec^2/deg R)
CVR	=	C_v	,	Specific heat at constant volume (3283.0 ft^2/sec^2/deg R)
EP	=	e'	,	2.7182818 (exponential)
GAMMA	=	γ	,	Ratio of specific heat (1.4)
GASR	=	R	,	Gas constant (1714.0 ft^2/sec^2/deg R)
PI	=	π	,	3.1415926
PRESR	=	P_r	,	Reference static pressure (psfa)
PRL	=	Pr_L	,	Prandtl number laminar 0.70
PRT	=	Pr_T	,	Prandtl number turbulent 0.72
RHØR	=	ρ_r	,	Reference density (slugs/ft^3)
SNDR	=	c_r	,	Reference speed of sound 1116.0 (ft/sec)
TEMPR	=	T_r	,	Reference temperature (deg rankin)
TI	=		,	(0.1745329 radians/deg)
VISCR	=	μ_r	,	Reference molecular viscosity (0.370×10^{-6})

LIST OF VARIABLES IN CØMMØN/CØRE/

Coordinate Functions

Q(1,K)	=	R	,	Radius (dimensionless)
Q(2,K)	=	Z	,	Axial distance (dimensionless)
Q(3,K)	=	$\partial R/\partial n$	,	Normal derivative of radius (dimensionless)
Q(4,K)	=	$\partial R/\partial S$	,	Streamwise derivative of radius (dimensionless)
Q(5,K)	=	$\cos^2\Theta$	,	Axisymmetric flow angle
Q(6,K)	=	V	,	Metric scale coefficient (dimensionless)
Q(7,K)	=	$\partial V/\partial n$	,	Curvature of streamline (dimensionless)
Q(8,K)	=	$\partial V/\partial S$	,	Curvature of potential line (dimensionless)
Q(9,K)	=	X	,	Distance along streamline (dimensionless)
Q(10,K)	=	Y	,	Physical distance across duct (dimensionless)
Q(11,K)	=	Y/Y_T	,	Fractional distance across duct (dimensionless)
Q(12,K)	=	A	,	Area between adjacent streamlines (dimensionless)
Q(13,K)	=	G	,	Gap between blade surfaces (dimensionless)
Q(14,K)	=	$\partial G/\partial n$	,	Normal derivative of blade surface (dimensionless)
Q(15,K)	=	$\partial G/\partial S$	,	Streamwise derivative of blade surface (dimensionless)
Q(16,K)	=	$\partial\eta/\partial n = \chi$	,	Transform of normal coordinate (dimensionless)
Q(17,K)	=	$\partial^2\eta/\partial n^2$	,	Second derivative (dimensionless)
Q(18,K)	=	n	,	Normal coordinate (dimensionless)
Q(19,K)	=	η	,	Transformed normal coordinate (dimensionless)
K	=	1,KL	,	Number of streamlines (dimensionless)

LIST OF VARIABLES IN CØMMØN/CØR2/

Caluclate Wall Values

RHS(1)	=	R_H	, Radius ID wall (dimensionless)
RHS(2)	=	dR_H/dZ	, Derivative (dimensionless)
RHS(3)	=	$-K_{HI}(S)$	, Input curvature at station S (dimensionless)
RHS(4)	=	Z_H	, Axial distance ID wall (dimensionless)
RHS(5)	=	V_H	, Metric coefficient ID wall (dimensionless)
RHS(6)	=	dV_H/dS	, Derivative (dimensionless)
RHS(7)	=	$dV_H/dn = -K$	, Derivative (dimensionless)
RHS(8)	=	X_H	, Arc length ID wall (dimensionless)
RHS(9)	=	$\mathring{m}_H$	, Mass flow bleed (dimensionless)
RHS(10)	=	Θ_H	, Wall temperature (dimensionless)
RMS(1)	=	R_{HI}	, Input radius ID wall (dimensionless)
RMS(2)	=	Z_{HI}	, Input axial distance ID wall (dimensionless)
RMS(3)	=	X_{HI}	, Input arc length ID wall (dimensionless)
RMS(4)	=	$-K_{HI}$	, Input wall curvature ID wall (dimensionless)
RMS(5)	=	R_{TI}	, Input wall radius OD wall (dimensionless)
RMS(6)	=	Z_{TI}	, Input wall axial length OD wall (dimensionless)
RMS(7)	=	X_{TI}	, Input wall arc length OD wall (dimensionless)
RMS(8)	=	$-K_{TI}$	, Input wall curvature OD wall (dimensionless)
RMS(9)			
RMS(10)			
RTS(1)	=	R_T	, Radius OD wall (dimensionless)
RTS(2)	=	dR_T/dZ	, Derivative (dimensionless)

CØMMØN/CØR2/ (Cont'd)

RTS(3)	=	$-K_{TI}(S)$	, Input curvature at station S (dimensionless)
RTS(4)	=	Z_T	, Axial Distance OD wall (dimensionless)
RTS(5)	=	V_T	, Metric coefficient (dimensionless)
RTS(6)	=	dV_T/dS	, Derivative (dimensionless)
RTS(7)	=	$dV_T/dn = -K$	, Derivative (dimensionless)
RTS(8)	=	X_T	, Arc length OD wall (dimensionless)
RTS(9)	=	$\mathring{m}_T$	, Mass flow bleed (dimensionless)
RTS(10)	=	Θ_T	, Wall temperature (dimensionless)

LIST OF VARIABLES IN CØMMØN/CSLØT/

Dimensionless Slot Geometry Variables

ALSLØT(N,2)	=	α_{SL}	, Slot swirl angle (rad)
HSLØT(N,L)	=	H_{SL}	, Slot height (dimensionless)
JLSLØT(N)	=		, Number of slots
LISZE(N,L)	=	0	, Small slot
	=	1	, Large slot
LSLØT(L,N)			, Slot index
POSLØT(N,L)	=	Π_{OSL}	, Slot total pressure (dimensionless)
TOSLØT(N,L)	=	Θ_{OSL}	, Slot total temperature (dimensionless)
ZSLØT(N,L)	=	Z_{SL}	, Axial slot location (dimensionless)

N = 1 Tip wall
  = 2 Hub wall

L = 1,15 Slot index

LIST OF VARIABLES IN CØMMØN/DERIV/

Strut Force Functions

DF(1,K) = $[H_s/XV]^{J}_{K-1/2}$, Streamwise strut force/volume (dimensionless)

DF(2,K) = $[H_\phi XV]^{J}_{K-1/2}$, Tangential strut force/volume (dimensionless)

DF(3,K) = $[\Phi_B/XV]^{J}_{K-1/2}$, Total pressure loss/volume (dimensionless)

DF(4,K) = $[X]^{J}_{K-1/2}$, Coordinate distortion (dimensionless)

DF(5,K) = $[H_s/XV]^{J-1}_{K-1/2}$, Streamwise strut force/volume (dimensionless)

DF(6,K) = $[H_\phi/XV]^{J-1}_{K-1/2}$, Tangential strut force/volume (dimensionless)

DF(7,K) = $[\Phi_B/XV]^{J-1}_{K-1/2}$, Total pressure loss/volume (dimensionless)

DF(8,K) = $[X]^{J-1}_{K-1/2}$, Coordinate distortion (dimensionless)

where

$$X = d\eta/dn$$

LIST OF VARIABLES IN CØMMØN/DSKB/

Parameters for I/O Routine

DSKLØC (UNIT)	=	N where:
UNIT	=	Unit number (See PARAMETER list)
N	=	Last block number read

LIST OF VARIABLES CØMMØN/DRED1/
CØMMØN/DRED2/

Coordinate Variables I/O

BLØCK(I)	I=1,ISL	Coordinates at J+1
BLØCK1(I)	I=1,ISL	Coordinates at J

See EQUIVALENCE statement.

where for J+1 station we have

JSTEP		J+1	,	Station or block number
Q2(I,J)	≡	Q(I,J)	,	See CØMMØN/CØRE/
RHS2(I)	≡	RHS(I)	,	See CØMMØN/CØR2/
RMS2(I)	≡	RMS(I)	,	See CØMMØN/CØR2/
RTS2(I)	≡	RTS(I)	,	See CØMMØN/CØR2
DSTEP	=	DS	,	Step Size in streamwise direction
QPARM(1)	=	r_r	,	Reference radius
QPARM(2)				
QPARM(3)	=	JL	,	No. streamwise stations
QPARM(4)	=	KL	,	No. streamlines
QPARM(5)				
QPARM(6)				
QPARM(7)				
QPARM(8)				
QPARM(9)				
QPARM(10)				

LIST OF VARIABLES IN CØMMØN/DUCØUT/

Calcualted Wall Coordinates

R(1,1,J)	=	$R_T(Z_J)$	,	Radius of hub (dimensionless)
R(2,1,J)	=	$R_H(Z_J)$	,	Radius of tip (dimensionless)
R(1,2,J)	=	$\mathring{m}_T(Z_T)$	,	Mass flow tip bleed (dimensionless)
R(2,2,J)	=	$\mathring{m}_H(Z_J)$	,	Mass flow of hub bleed (dimensionless)
R(1,3,J)	=	$\Theta_H(Z_J)$	,	Wall temperature of tip (dimensionless)
R(2,3,J)	=	$\Theta_T(Z_J)$	,	Axial distance of hub (dimensionless)
R(1,3,J)	=	Z_T	,	Axial distance tip (dimensionless)
R(2,3,J)	=	Z_H	,	Axial distance hub (dimensionless)

LIST OF VARIABLES IN CØMMØN/DUCTIN/

Input Duct and Flow Data

AINI(L)	=	AINPUT(I,J,K)	, See CØMMØN/SPIØ/
BINI(L)	=	BINPUT(I,J,K)	, See CØMMØN/SPIØ/
I	=	1,5	
J	=	1,2	
K	=	1,KLL	
L	=	5*(K-1)+I+(J-1)*5*KLL	
DUCTI(I) I	=	1,15	, Arbitrary duct geometry parameters
RD1I(L)	=	R(1,1,L)*RADR,	Tip wall coordinates (ft)
RD2I(L)	=	R(1,2,L)*RADR,	Hub wall coordinates (ft)
ZD1J(L)	=	R(4,1,L)*RADR,	Tip wall coordinates (ft)
ZD2J(L)	=	R(4,2,L)*RADR,	Hub wall coordinates (ft)
L	=	1, JL	

LIST OF VARIABLES IN CØMMØN/FCØR/

Mass Flow Weighted Flow Errors

EAP	=	$\varepsilon_{u\phi}$	,	Error in swirl velocity
EAS	=	ε_{Us}	,	Error in streamwise velocity
EEN	=	ε_{I}	,	Error in Entropy
EPO	=	$\varepsilon_{\pi o}$	,	Error in total pressure
ESI	=	ε_{ψ}	,	Error in mass flow
ETO	=	$\varepsilon_{\pi o}$	,	Error in total pressure

LIST OF VARIABLES IN CØMMØN/FIVC/

Inviscid Flow Variables I/O

FIV(1,L,K)	=	ψ	,	Stream function (dimensionless)
FIV(2,L,K)	=	U_s	,	Streamwise velocity (dimensionless)
FIV(3,L,K)	=	U_ϕ	,	Tangential velocity (dimensionless)
FIV(4,L,K)	=	Π	,	Static pressure (dimensionless)
FIV(5,L,K)	=	I	,	Entropy (dimensionless)
FIV(6,L,K)	=	Θ	,	Static temperature (dimensionless)
FIV(7,L,K)	=	P	,	Density (dimensionless)
FIV(8,L,K)	=	M	,	Mach number
FIV(9,L,K)	=			
FIV(10,L,K)	=			

L=1	@	J-1	station
L=2	@	J	station
L=3	@	J+1	station
K=1,KL			streamlines

FIPARM(1)	=	ρ_r	,	Reference density (slugs/ft^3)
FIPARM(2)	=	T_r	,	Reference temperature (deg R)
FIPARM(3)	=	P_r	,	Reference pressure (psfa)
FIPARM(4)	=	g	,	Gravitational constant (ft/sec^2)
FIPARM(5)	=	μ_r	,	Reference viscosity (slugs/ft/sec)
FIPARM(6)	=	C_p	,	Specific heat constant pressure (ft^2/sec^2/deg)
FIPARM(7)	=	C_v	,	Specific heat constant volume (ft^2/sec^2/deg)
FIPARM(8)	=	R	,	Gas constant (ft^2/sec^2/deg)

FIPARM(9)	=	Pr_T	,	Prandtl number (turbulent)
FIPARM(10)				
FIPARM(11)	=	u_r	,	Reference velocity (ft/sec)
FIPARM(12)		NØPT7		Number of stations stored in inviscid solver
FIPARM(13)				
FIPARM(14)		IØPT15		First station
FIPARM(15)		IØPT16		Last station

LIST OF VARIABLES IN CØMMØN/FLAGS/

Internal Flags

NØPTØ where Ø = 1,17 , Flags to regulate calculation*

*See section 6.3 List of Flags for Options

LIST OF VARIABLES IN CØMMØN/FLØWI/

Internal Flow Variables

FG(1,K)	=	α	,	Inlet swirl angle (deg)
FG(2,K)	=	Π_o	,	Inlet stagnation pressure (dimensionless)
FG(3,K)	=	Θ_o	,	Inlet stagnation temperature (dimensionless)
FG(4,K)	=	M	,	Inlet Mach number (dimensionless)
FG(5,K)	=	P_o	,	Inlet stagnation density (dimensionless)
FG(6,K)	=	U	,	Inlet magnitude of velocity (dimensionless)
K	=	1, KL	,	Number of streamlines

LIST OF VARIABLES IN CØMMØN/FØRS/

Calculated Blade Force Variables

FØRC(1,K)	=	H_s	,	Streamwise force/area (dimensionless)
FØRC(2,K)	=	H_ϕ	,	Swirl force/area (dimensionless)
FØRC(3,K)	=	Ξ_s	,	Streamwise force/span (dimensionless)
FØRC(4,K)	=	Ξ_ϕ	,	Swirl force/span (dimensionless)
FØRC(5,K)	=	Φ_B	,	Blade dissipation/area (dimensionless)
FØRC(6,K)	=	$\mathcal{D}$	,	Blade dissipation/span (dimensionless)
K	=	1,KL	,	Number of streamlines (dimensionless)

LIST OF VARIABLES IN CØMMØN/FØRS2/

Blade Force Variables

FF(1,I,K)	=	$\hat{M}$	, Inviscid Mach number (dimensionless)
FF(2,I,K)	=	$\hat{\Pi}$	, Inviscid static pressure (dimensionless)
FF(3,I,K)	=	$\hat{\Theta}$	, Inviscid static pressure (dimensionless)
FF(4,I,K)	=	$\hat{\Theta}_o$	, Inviscid total temperature (dimensionless)
FF(5,I,K)	=	$\hat{\Pi}_o$	, Inviscid total pressure (dimensionless)
FF(6,I,K)	=	$\hat{P}$	, Inviscid density (dimensionless)
FF(7,I,K)	=	$\hat{U}_s$	, Inviscid streamwise velocity (dimensionless)
FF(8,I,K)	=	$\hat{U}_\phi$	, Absolute swirl velocity (dimensionless)
FF(9,I,K)	=	$\hat{W}_\phi$	, Relative swirl velocity (dimensionless)
FF(10,I,K)	=	$\hat{R}$	, Radius (dimensionless)
FF(11,I,K)	=	$\hat{\alpha}$	, Absolute angle to axis (deg)
FF(12,I,K)	=	$\hat{\beta}$	, Relative angle to axis (deg)
FF(13,I,K)	=	$\hat{I}$	, Inviscid flow entropy (dimensionless)
FF(14,I,K)	=	$\hat{U}$	, Magnitude of absolute inviscid flow velocity (dimensionless)
FF(15,1,K)	=	$\hat{Z}_B$	, Loss coefficient (dimensionless)
FF(15,2,K)	=	$\Delta\hat{I}_B$	, Blade entropy rise (dimensionless)
FF(16,1,K)	=	$\hat{\psi}$	, Stream function (dimensionless)
FF(17,1,K)	=	C_L	, Lift coefficient (dimensionless)
FF(17,2,K)	=	C_D	, Drag coefficient (dimensionless)
I	=	1	, Upstream of blade row
I	=	2	, Downstream of blade row
K	=	1, KL	, Number of streamlines

LIST OF VARIABLES IN CØMMØN/FUNC/

Viscous Flow Variables

F(1,1,K)	=	Ψ	, Stream function J=1 (dimensionless)
F(2,1,K)	=	Θ_o	, Total temperature J=1 (dimensionless)
F(3,1,K)	=	Π_o	, Total pressure J=1 (dimensionless)
F(4,1,K)	=	ΔI	, Entropy rise along Ψ_K^J (dimensionless)
F(5,1,K)	=	$\Delta\Theta_o$	, Total temperature rise along Ψ_K^J (dimensionless)
F(6,1,K)	=		, Not used
F(7,1,K)	=		, Not used
F(8,1,K)	=	K^J	, Turbulent kinetic energy at J (dimensionless)
F(9,1,K)	=	E^J	, Turbulent dissipation at J (dimensionless)
F(10,1,K)	=	μ_E^J/μ_r	, Effective viscosity at J (dimensionless)
F(1,N,K)	=	Ψ	, Stream function (dimensionless)
F(2,N,K)	=	U_s	, Streamwise velocity (dimensionless)
F(3,N,K)	=	U_ϕ	, Tangential velocity (dimensionless)
F(4,N,K)	=	Π	, Static pressure (dimensionless)
F(5,N,K)	=	I	, Entropy (dimensionless)
F(6,N,K)	=	Θ	, Static temperature (dimensionless)
F(7,N,K)	=	P	, Density (dimensionless)
F(8,N,K)	=	Σ_{ns}	, Streamwise stress (dimensionless)
F(9,N,K)	=	$\Sigma_{n\phi}$	, Tangential stress (dimensionless)
F(10,N,K)	=	Q	, Heat flux (dimensional)

N = 2 for station J

= 3 for station J+1

K = 1, KL

CØMMØN/FUNC/ (Cont'd)

FPARM(L)	=	P_r	,	Reference density (slugs/ft^3)
FPARM(2)	=	T_r	,	Reference temperature (deg R)
FPARM(3)	=	P_r	,	Reference pressure (psfa)
FPARM(4)	=	g	,	Gravitational constant (ft/sec^2)
FPARM(5)	=	μ_r	,	Reference viscosity (slug/ft/sec)
FPARM(6)	=	C_p	,	Specific heat (ft^2/sec^2/deg R)
FPARM(7)	=	C_v	,	Specific heat (ft^2/sec^2/deg R)
FPARM(8)	=	R	,	Gas constant (ft^2/sec^2/deg R)
FPARM(9)	=	Pr_T	,	Turbulent Prandtl number
FPARM(10)	=		,	Not used
FPARM(11)	=	u_r	,	Reference velocity (ft/sec)
FPARM(12)	=	NØPT7	,	No. blocks stored in Inviscid solver
FPARM(13)	=	NØPT8	,	No. blocks stored in viscous solver
FPARM(14)	=	IØPT15	,	First station
FPARM(15)	=	IØPT16	,	Last station

LIST OF VARIABLES IN CØMMØN/INTINP/

Mesh Parameters, Input Options, Debug Options

IDBGØ	Ø = 1,20	, Debug options see section 4.3
IØPTØ	Ø = 1,20	, Input options see section 4.2
JFIRST		, First streamwise station
JL		, No. of streamwise stations
JLAST		, Last streamwise station
JLEDG		, Blade leading edge
JLPTS		, No. wall input data points
JSEP		, No. stored blocks viscous solution
JTEDG		, Blade trailing edge station
KDS		, No. of steps/station
KL		, No. streamlines
KLL		, No. of input flow data points

LIST OF VARIABLES IN CØMMØN/MATRXA/

Variables for Viscous Flow Matrix Equations

AE(I,J,K)	=	E_{IJ}	, Element of E matrix in SØLVI
AZ(I,K)	=	Z_I	, Element of Z vector in SØLVI
BA(I,K)	=	B_I	, See SØLVI
FV(I,J,K)	≡	F(I,J,K)	, Solution from global iteration SØLVI

LIST OF VARIABLES IN CØMMØN/NGTERM/

Variables for Neglected Terms Calculation

VARBL(I,J,K) , See subroutine VARFVN

UN(K) = U_n , Normal velocity (dimensionless)

K = 1,KL

LIST OF VARIABLES IN CØMMØN/REALIN/

Input Flow Properties, Gas Properties

ACHI	χ	, Clauser constant
AKI	κ	, Von Kasmen constant
ALP1	α_1	, Inlet swirl angle (deg)
AMS1	M_{s1}	, Inlet mach number
ANH	n_H	, Power law ID wall
ANT	n_T	, Power law OD wall
API	A^+	, Van Driest constant
CPRI	C_p	, Specific heat constant pressure ($ft^2/sec^2/deg$)
CVRI	C_v	, Specific heat constant volume ($ft^2/sec^2/deg$)
DDS		, Distortion parameter
DSHI	δ_H	, Displacement thickness ID wall (ft)
DSTI	δ_T	, Displacement thickness OD wall (ft)
PRESO	P_o	, Total pressure (psfa)
PRLI	Pr_L	, Prandtl number laminar
PRTI	Pr_T	, Prandtl number turbulent
TEMPO	T_o	, Total temperature (deg R)
VISCRI	μ_r	, Reference viscosity (slug/ft/sec)

LIST OF VARIABLES IN CØMMØN/SPCFD/

Variables in Poisson Equation

F(K,J)	=	$1/(PV)_K^J$	,	Coefficients of Poisson equation
P(K,J)	=	Ψ_K^J	,	Stream function

LIST OF VARIABLES IN CØMMØN/SPCGD/

Variables for Streamline Curvature Calculation

F(K)	=	$1/(PV)_K$	, Coefficient of Poisson equation
G(K)	=	$V/(GP)_K$	, Coefficient for velocity
P(K)	=	P_K	, Density ratio (ρ/ρ_r)
T(K)	=	Θ_K	, Temperature ratio (T/T_r)
V(K)	=	V_K	, Metric coefficient

LIST OF SYMBOLS IN CØMMØN/SPIØ/

Initial Flow Variables, Mass Average Variables

AINPUT(1,J,K)	=	Y/Y_T	,	Spanwise location (dimensionless)
AINPUT(2,J,K)	=	Π_o	,	Total pressure (lb/ft^2 abs)
AINPUT(3,J,K)	=	Π	,	Static pressure (lb/ft^2 abs)
AINPUT(4,J,K)	=	α	,	Swirl angle (deg to axis)
AINPUT(5,J,K)	=	Θ_o	,	Total temperature (deg R)
J	=	1	,	Upstream
J	=	2	,	Downstream of blade row (dimensionless)
K	=	1,KLL	,	Number of spanwise stations
AVE(1,J)	=	ψ	,	Mass flow (dimensionless)
AVE(2,J)	=	$\bar{U}_S$	,	Average streamwise velocity (dimensionless)
AVE(3,J)	=	$\bar{U}_\phi$	,	Average swirl velocity (dimensionless)
AVE(4,J)	=	$\bar{\Pi}$	,	Average entropy (dimensionless)
AVE(5,J)	=	$\bar{I}$	,	Average entropy (dimensionless)
AVE(6,J)	=	$\bar{\Theta}$	,	Average static temperature (dimensionless)
AVE(7,J)	=	$\bar{P}$	,	Average density (dimensionless)
AVE(8,J)	=	$\bar{M}$	,	Average Mach number (dimensionless)
AVE(9,J)	=	$\bar{\Pi}_o$	,	Average total pressure (dimensionless)
AVE(10,J)	=	$\bar{\Theta}_o$	,	Average total temperature (dimensionless)

LIST OF VARIABLES IN CØMMØN/SPIØ/

BINPUT(2,J,K)	=	Π_o	,	Total pressure (lb/ft^2 abs)
BINPUT(3,J,K)	=	Π	,	Static pressure (lb/ft^2 abs)
BINPUT(4,J,K)	=	α	,	Swirl angle (deg to axis)
BINPUT(5,J,K)	=	Θ_o	,	Total temperature (deg R)
J	=	1	,	Inlet flow
J	=	2	,	Exit flow
K	=	1,KLL	,	Number of spanwise stations

LIST OF VARIABLES IN CØMMØN/STRES/

Geometric Functions

G(1,K) = $\left[G/V\right]^{J}_{K-1/2}$

G(2,K) = $\left[XV\right]^{J}_{K-1/2}$

G(3,K) = $\left[G(XV)\right]^{J}_{K-1/2}$

G(4,K) = $\left[\frac{1}{XV}\,\frac{bV}{\partial n}\right]^{J}_{K-1/2}$

G(5,K) = $\left[\frac{1}{XR}\,\frac{\partial R}{\partial n}\right]^{J}_{K-1/2}$

G(6,K) = $\left[\frac{1}{XR}\,\frac{\partial R}{\partial S}\right]^{J}_{K-1/2}$

G(7,K) = $\left[\frac{V}{XG}\,\frac{\partial}{\partial n}\left(\frac{G}{V}\right)\right]$

G(8,K) = $\left[\frac{V}{XG}\,\frac{\partial}{\partial n}\left(\frac{G}{V}\right) - \frac{1}{XY}\,\frac{\partial V}{\partial n}\right]^{J}_{K-1/2}$

G(9,K) = $\left[\frac{V}{XG}\,\frac{\partial}{\partial n}\left(\frac{G}{V}\right) - \frac{1}{XR}\,\frac{\partial R}{\partial n}\right]^{J}_{K-1/2}$

G(9+I,K) = G(I,K) @ J-1, I=1,9

where

$X = d\eta/dn$

LIST OF VARIABLES IN CØMMØN/STRMES/

Poisson Solver Stretching Parameter

BPØIS	=	B	, Stretching parameter
BPØISI	=	B_I	, Input stretching parameter

LIST OF VARIABLES IN CØMMØN/SVARB/

Mesh Variables, Flow Variables

AMACHR	=	M_r	, Reference mach number
AMACH1	=	M_1	, Average inlet mach number
APRES1	=	$\bar{P}_1$	, Average inlet static pressure (psfa)
APRO1	=	$\bar{P}_{o1}$	, Average inlet total pressure (psfa)
AREAR	=	r_r^2	, Reference area (ft^2)
AREA1	=	a_1	, Inlet area (ft^2)
ATEMP1	=	$\bar{T}_1$	, Average inlet static temperature (deg R)
DELO	=	δ_o^*/r_r	, Average displacement thickness
DETA	=	$\Delta\eta$	, Transverse step size
DRØUGI	=	d	, Equivalent sand roughness (in. microns)
DS	=	Δs	, Streamwise step coarse grid
DSS	=	ds	, Streamwise step fine grid
DSH	=	δ_H^*/r_r	, Inlet displacement thickness ID wall
DST	=	δ_T^*/r_r	, Inlet displacement thickness OD wall
DYNP1	=	$\bar{q}_1$	, Average inlet dynamic pressure (psfa)
DZ	=	$\Delta z/r_r$	, Step size in axial distance (dimensionless)
ERRBKN	=	ε_B	, Error in back pressure iteration
ERRPIN	=	ε_p	, Error in normal static pressure
GMR1	=	$(\gamma-1)M_p^2$	
GMR2	=	γM_r^2	

LIST OF VARIABLES IN CØMMØN/SVARB/

RADR	=	r_r	, Reference radius (ft)
REY	=	Re_r	, Reynolds number
RHØO	=		, Not used
SL	=	s_L	, Streamwise coordinate length
USR	=	u_r	, Reference velocity (ft/sec)
USTARH	=	u_H^*/u_r	, Friction velocity ID wall
USTART	=	u_T^*/u_r	, Friction velocity OD wall
WFLI	=	w_I	, Input weight flow (lb/sec)
WFLO	=	w	, Calculated weight flow (lb/sec)
Z1	=	z_1	, Axial length of duct (ft)

LIST OF VARIABLES IN CØMMØN/TETLIN/

TITLE(12)	Input title card

LIST OF VARIABLES IN CØMMØN/TRBL/

AMUE(K)	=	μ_E/μ_r	, Effective viscosity
AMUL(K)	=	μ/μ_r	, Molecular viscosity
AMUT(K)	=	μ_T/μ_r	, Turbulent viscosity
TRB(1,1,K)	=	K_K^{J-1}	, Turbulence kinetic energy (k/u_r^2)
TRB(1,2,K)	=	K_K^J	, Turbulence kinetic energy (k/u_r^2)
TRB(1,3,K)	=	$(K_K^J)^\mu$	, Turbulence kinetic energy (k/u_r^2)
TRB(2,1,K)	=	E_K^{J-1}	, Turbulence dissipation $(\rho r/\mu_r(r_r/u_r)^2\varepsilon)$
TRB(2,2,K)	=	E_K^J	, Turbulence dissipation $(\rho r/\mu_r(r_r/u_r)^2\varepsilon)$
TRB(2,3,K)	=	$(E_K^J)^\mu$	, Turbulence dissipation $(\rho_r/\mu_r/(r_r/u_r)^2\varepsilon)$
C1		C_1	, Constant
C2		C_2	, Constant
SIGE		σ_E	, Constant
SIGK		σ_k	, Constant
NTVRB2			, Flag
CDAMP		C_m	, Constant

LIST OF VARIABLES IN CØMMØN/TVRBS/

Turbulent Viscosity, Conductivity

DHF(1,K) , Not used

DHF(2,K) = $(\mu_E/\mu_r)^{J-1}_{K+1/2}$, Effective viscosity

DPF(1,K) , Not used

DPF(2,K) = $\left(\frac{1}{Pr_T}\frac{\mu_E}{\mu_r}\right)^{J-1}_{K+1/2}$, Effective conductivity

LIST OF VARIABLES IN CØMMØN/TURB2/

DDSTRM	=	$(\Delta\delta^*)_u$	, Minimum change in δ^x
DELØR	=	$(\Delta X/\delta^*)_m$	, Maximum step size
DSIGM	=	$(\Delta\Sigma)_m$	, Maximum change in wall stress
EVSVSM	=	$\varepsilon(U_s^{\,2})_m$	, Maximum error in Us

LIST OF SYMBOLS IN CØMMØN/WLINE/

Variables for Locating Arbitrary Line

BLNE(1,L)	=	$\bar{R}_L$	,	Radius (dimensionless)
BLNE(2,L)	=	$\bar{Z}_L$	,	Axial location (dimensionless)
BLNE(3,L)	=	$\bar{X}_L$	,	Streamline distance (dimensionless)
BLNE(4,L)	=	$\bar{S}_L$	,	Streamwise coordinate (dimensionless)
BLNE(5,L)	=	n_L	,	Normal coordinate (dimensionless)
JKLNE(1,L)	=	J_L	,	J index corner point
JKLNE(2,L)	=	K_L	,	K index corner point
LLAST			,	Number of input points
L	=	1,LLAST		

LIST OF SYMBOLS IN CØMMØN/ZFØU/

Variables for Output Data Line Calculation

FI(1,L)	=	ψ	, Stream function (dimensionless)
FI(2,L)	=	U_s	, Streamwise velocity (dimensionless)
FI(3,L)	=	U_ϕ	, Swirl velocity (dimensionless)
FI(4,L)	=	Π	, Static pressure (dimensionless)
FI(5,L)	=	I	, Entropy (dimensionless)
FI(6,L)	=	Θ	, Static temperature (dimensionless)
FI(7,L)	=	$\underline{P}$	, Density (dimensionless)
FI(8,L)	=	Σ_{ns}	, Streamwise stress (dimensionless
FI(9,L)	=	$\Sigma_{n\phi}$	, Tangential stress (dimensionless)
FI(10,L)	=	Q	, Heat flux (dimensionless)
FI(11,L)	=	U_n	, Normal velocity (dimensionless)

where L = 1,NLAST Output data points

LIST OF SYMBOLS IN CØMMØN/XFØU/

Parameters for Output Data Line Calculation

FI1(1)	=	$\psi(S_J,N_L)$	,	Stream function (dimensionless)
FI1(2)	=	$U_S(S_J,N_L)$	,	Streamwise velocity (dimensionless)
FI1(3)	=	$U_\phi(S_J,N_L)$	,	Swirl velocity (dimensionless)
FI1(4)	=	$\Pi\ (S_J,N_L)$	,	Static pressure (dimensionless)
FI1(5)	=	$I\ (S_J,N_L)$	,	Entropy (dimensionless)
FI1(6)	=	$\Theta(S_J,N_L)$	,	Static temperature (dimensionless)
FI1(7)	=	$\underline{P}\ (S_J,N_L)$	,	Density (dimensionless)
FI1(8)	=	$\Sigma_{ns}\ (S_J,N_L)$	,	Streamwise stress (dimensionless)
RI1(9)	=	$\Sigma_{n\phi}\ (S_J,N_L)$	,	Tangential stress (dimensionless)
FI1(10)	=	$Q\ (S_J,N_L)$	,	Heat flux (dimensionless)
FI1(11)	=	$U_n\ (S_J,N_L)$	,	Normal velocity (dimensionless)
FI2(N)	=	FI1(N) at S_{J+1} , N_L		

where

S_J = streamwise coordinate at station J

S_{J+1} = streamwise coordinate at station J+1

N_L = normal coordinate for output data point L

7.0 DETAILED DESCRIPTION OF ADD CODE

7.1 List of Subroutines and Functions

Name	Object
ALINE	Find intersection of output data line with wall
ALTMN	Main Program (see Section 5.1)
AMF	Calculate Mach number from area ratio
AMFØR	Find stream thrust average
AMINLT	Compute Mach number from mass flow
AMU	Compute molecular viscosity (function)
BAMFØR	Compute choked weight flow and stream thrust
BLDGØM	Locate blade centerline in (n,s) coordinates
BLINE	Calculate neighboring points on output line
BLKDAT	Set program constants in BLOCK DATA
BLKRED	Read/write data blocks on data files
BLPARM	Computer boundary layer parameters
BPLUSR	Rough wall integration constant
CALINV	Calculate inviscid flow solution
CASC	Calculate cascade performance
CDS	Calculate Roberts mesh distortion parameter (function)
CFCØLE	Calculate Coles' friction coefficient (function)
CKINPT	Check input data for radial equilibrium
CLINE	Calculate (n,s) coordinates for point (R,Z)
CØØR	Interpolate coordinates in streamwise direction
CØØRST	Controls flow of coordinate calculation
CØØR1	Computer approximate coordinate functions

Name	Object
CØØR2	Calculate wall curvature and arc length
CØØR3	Compute coordinate functions
CØØR4	Find Schwartz Christoffel parameters
CØØR5	Interpolate wall curvature at station S
CPLX1	Real and imaginary parts Schwartz-Christoffel transform
CRØSS1	Find intersection of two straight lines
CRØSS2	Search coordinate rectangle for crossing point
DEFFIL	Define random access data files (IBM version)
DLINE	Store coordinates of output data line
DRØBRT	Computation of derivative of Robert's transformation (function)
DUMIØ	Read/write random access data files (IBM version)
ECØINP	Write input data
ELINE	Extrapolate for end points on output data line
ERPIN	Compute error in normal pressure gradient
EWLØSS	Calculate end wall loss
FAVER	Solve for mass flow weighted average flow
FCØLES	Compute Cole's velocity profile (function)
FCØRCT	Correct solution based on mass flow average
FCPLX	Evaluate Schwartz Christoffel transformation
FETA	Calculate distorted mesh to be used in POIS
FINTG	Integrate equations of Schwartz Christoffel transformation
FINVIS	Calculate upstream/downstream force variables

Name	Object
FLINE	Find coordinates of output data line
FLØWIN	Set initial flow conditions
FNØRM	Normalize input variables
FØRCE	Compute blade force/span
FØRCL	Computer blade force/volume
FØUTP	Interpolate solution on output data line
FTHIK	Calculate blade thickness
GBLADE	Calculate blade geometry
GDUCT	Prescribe duct shape
INIT	Set all CØMMØN block variables to zero
INITF	Initialize data file parameters for inviscid solution
INITFV	Initialize data file parameters for viscous solution
INITQ	Initialize data file parameters for Q array
INTFRE	Initialize freestream conditions
IZERØ	Set integer variables to zero
MINVRT	Invert MxN matrix
ØRTFUN	Set up coordinate functions used in SØLVI
ØUTPUT	Print title page
PØIS	Solve Poisson equation
PØISCF	Setup coefficients for POIS
PØISØN	Calculate axisymmetric streamline curvature
PRTØUT	Calculate and print terms neglected in ADD code equations

Name	Object
QINTER	Interpolate curvature from PØIS to mesh to SØLVI mesh
QPTMAX	Calculate maximum total and dynamic pressure
RDCØR	Read J and J+1 coordinate block
READPF	Read P and F files in NIST word blocks
READPG	Read variables for curvature calculation
RECØRD	Calculate record numbers
REDINP	Read input parameters and variables
RØBRTS	Calculate distorted mesh using Robert's transformation(function)
SCURVA	Calculate curvature from potential flow solution
SLETE	Find indices for strut control surface
SLØTA	Construct duct with slots
SLTFLØ	Compute slot inlet flow
SMØØTH	Smooth wall contour
SØLVI	Integrate equations of motion
STRESI	Initial stress and heat flux
SUBLAY	Initialize K,E turbulence model in inner layer
TPRINT	Print computer time
TRBLADE	Transform from stacking plane to duct plane
TRLETE	Find leading and trailing edge in stacking plane
TURB	Compute turbulent viscosity using algebraic turbulence model
TURB2Q	Calculate turbulent viscosity using K,E turbulence model
UBLAS	Blasius' velocity profile (function)

Name	Object
UMACH	Calculate inviscid velocity
VARFUN	Store variables to be used by PRTØUT
WBLEED	Calculate perforated wall bleed
WFITER	Inlet weight flow iteration
WRITPF	Store updated potential flow solution
WRTBLD	Write output for WBLEED
WRTCAL	Write output for CALINV
WRTCKI	Write output for CKINPT
WRTFØU	Print solution on output data line
WRTGDC	Write output summary - coordinate calculation
WRTINP	Write input parameters and variables
WRTSØV	Print solution at selected stations
WRTSUM	Write output summary papers
XH	Calculate arc length hub wall
XT	Claculate arc length tip wall
ZERØ	Set real variables to zero

7.2 Detail Description of Subroutines

Subroutine ALINE (IWALL, JBLN, RX, ZX, XX)

Object

Find intersection of output data line with the wall

Options

IWALL	= 1	OD WALL
	= 2	ID WALL

List of Symbols

JBLN		, Intersection occurs between JBLN, JBLN+1
(R1,Z1,R2,Z2)	= (R_1, Z_1, R_2, Z_2)	, Neighboring points on wall (dimensionless)
(RB1,ZB1,RB2,ZB2)	= $(\bar{R}_1, \bar{Z}_1, \bar{R}_2, \bar{Z}_2)$	, Neighboring points on input line (dimensionless)
RX,ZX	= R,Z	, Coordinates of intersection (dimensionless)
XX	= X	, Distance along wall to intersection (dimensionless)

Theory

The wall coordinates are searched for the intersection of the wall and output data line. This intersection must occur within the pair of points (RB1,ZB1) and (RB2,ZB2). If this intersection does not occur within the coordinate mesh, DIAGNØSTIC No. 39 is printed and the program stops. If an intersection of the wall and the extrapolated output data line occurs, this intersection (RX,ZX) is printed.

Subroutine AMF (AA, AM1, AMG, AM, ACPC, ACPI)

Object

Calculate Mach Number from Area Ratio

Options

AMG < 1 Subsonic Solution
> 1 Supersonic Solution

List of Symbols

AA	$= A/A_1$	, Area ratio
ACPC	$= C_{PC}$	, Pressure coefficient (compressible)
ACPI	$= C_{PI}$	, Pressure coefficient (incompressible)
AM	$= M$	, Mach number
AMG	$= M_G$	, Initial guess for Mach number
AM1	$= M_1$	, Mach number at inlet
	γ	, Ratio of specific heat
	P_o/P	, Total to static pressure ratio

Theory

For one dimensional isentropic flow the area ratio is related to the Mach number by (see Ref. 1),

$$\frac{A}{A_1} = \frac{M_1}{M} \cdot \left[\frac{1 + \frac{\gamma-1}{2} M^2}{1 + \frac{\gamma-1}{2} M_1^2}\right]^{\frac{\gamma+1}{2(\gamma-1)}} \tag{1}$$

Eq. (1) has a minimum at $M = 1$. This subroutine first checks to see if the area ratio is less than this minimum. If the area ratio is less than the minimum it returns $M = 1.0$. If the area ratio is greater than the minimum, then it solves for M given A_2/A_1 and M_1 using Newton's method. Either the subsonic or supersonic root is possible dependent on the value of the input AMG. Once the Mach number iteration converges, the pressure is given by

$$\frac{P_o}{P} = \left[1 + \frac{\gamma-1}{2} M^2\right]^{\gamma/\gamma-1} \tag{2}$$

and the pressure coefficients are given by

$$C_{PI} = 1 - \left(\frac{A_1}{A}\right)^2 \tag{3}$$

$$C_{PC} = \frac{P/P_o - P_1/P_o}{1 - P_1/P_o} \tag{4}$$

References

1. Shapiro, A. H.: The Dynamics and Thermodynamics of Compressible Fluid Flow, Vol. 1, Ronald Press Co., New York, 1953.

Subroutine AMFØR(AW,AF,AA,AM,APR,APRO)

Object

Find stream thrust average properties

Options

None

List of Symbols

AA	$= A$	, Area $(a/(r_r^{2}))$
AF	$= \tilde{F}_T$	, Stream thrust $(f_T/(P_r\ r_r^{2}))$
AM	$= \hat{\tilde{M}}$	, Stream thrust average Mach number
AN	$= N$	, Mach number function
AW	$= \tilde{W}$	, Reduced mass flow $(M_r W/(\rho_r u_r r_r^{2})\ \tilde{\Theta}_o^{1/2})$
APR	$= \tilde{\Pi}$	; Stream thrust average static pressure $(\tilde{\rho}/\rho_r)$
APRO	$= \tilde{\Pi}_o$	, Stream thrust average total pressure $(\tilde{\rho}/\rho_r)$
	Θ_o	, Mass flow average total temperature $(\bar{T}_c/T_r)$

Theory

The stream thrust and reduced mass flow (Ref. 1) can be related to one dimensional average flow parameters by the relations

$$\tilde{F}_T = \tilde{\Pi}\left[1 + \gamma\hat{\tilde{M}}^2\right] A \qquad (1)$$

$$\hat{W} = \hat{\Pi}\hat{\tilde{M}}/\bar{\Theta}_o^{\,1/2} A \qquad (2)$$

Then

$$N = \tilde{F}_T/\tilde{W} = \tilde{M}\left[1 + \frac{\gamma-1}{2}\hat{M}^2\right]^{1/2} \Big/ \left[1 + \gamma\hat{M}\right] \qquad (3)$$

Eq. (3) has a minimum at $\tilde{M} = 1$. If the input N is less then this minimum, the subroutine returns DIAGNØSTIC NO. 03. If N is greater than the minimum, Eq. (3) is solved for $\tilde{M}$ using Newton's method. The stream thrust average static and total pressure is then given by

$$\tilde{\Pi} = F_T / [1 + \gamma \tilde{M}^2]/A \tag{4}$$

$$\tilde{\Pi}_o = \tilde{\Pi} \left[1 + \frac{\gamma-1}{2} \tilde{M}^2\right]^{\gamma/(\gamma-1)} \tag{5}$$

References

1. Shapiro, A. H.: The Dynamics and Thermodynamics of Compressible Fluid Flow Vol. 1, Ronald Press Co, New York 1953.

Subroutine AMINLT (WFL,PO,TO,ALI,AMI,PI)

Object

Compute Mach number form mass flow

Options

None

List of Symbols

AINLET = A , Area (ft^2)

ALI = α_1 , Inlet swirl angle (deg)

AMI = M , Inlet Mach number

AN = D , Mach number function

PO = P_o , Total pressure (psfa)

Pl = P , Static pressure (psfa)

TO = T_o , Total temperature (deg. R)

WFL = w , Weight flow (lb/sec)

Π_o , Total pressure ratio (P_o/P_r)

Θ_o , Total temperature ratio (T_o/T_r)

Theory

For average inlet conditions, the Mach number is related to the weight flow by the relation (see Ref. 1),

$$D = w/(g\rho_r C_n \Pi_o \Theta_o^{-1/2} A)$$

$$= M \left[1 + \frac{\gamma-1}{2} M^2\right]^{-\frac{\gamma+1}{2(\gamma-1)}} \qquad (1)$$

The Mach number function D(M) has a maximum at M = 1. If the specified weight flow is greater than this maximum, the subroutine returns DIAGNØSTIC No. 2. If it is less, then Eq. (1) is solved for M using Newton's method.

Function AMU(T)

Object

Compute Molecular Viscosity

Options

None

List of Symbols

AMU = μ/μ_r, Ratio of Molecular Viscosity (dimensionless)

T = θ , Static temperature Ratio (dimensionless)

Theory

The molecular viscosity is computed according to Sutherland's formula (Ref. 1). The working fluid is assumed to be air. Accordingly,

$$\frac{\mu}{\mu r} = \Theta^{3/2} \frac{1 + 198.0/T_r}{\Theta + 198.0/T_r} \qquad (1)$$

References

1. Schlicting, H.: Boundary Layer Theory. 6th Ed., McGraw-Hill, New York, 1968.

Subroutine BAMFØR

Object

Calculate choked weight flow and stream thrust

Options

None

List of Symbols

AM = $\tilde{M}$, Stream thrust average Mach number

APR = $\tilde{\Pi}$, Stream thrust average static pressure ($\tilde{P}/P_r$)

APRO = $\tilde{\Pi}_o$, Stream thrust average total pressure ($\tilde{P}_T/P_r$)

ARO = A , Area (a/r_r^2)

AW = $\tilde{W}$, Reduced mass flow ($M_r w/(\rho_r u_r r_r^2) \Theta_o^{1/2}$)

DAPRO= $\Delta\tilde{\Pi}_o$, Mean deviation total pressure

DFO = $\Delta\tilde{F}_T$, Mean deviation stream thrust

DTO = $\Delta\tilde{}_o$, Mean deviation total temperature

FO = $\tilde{F}_T$, Stream thrust ($f_T/(P_r r_r^2)$)

STRT = f_T , Stream thrust (lb)

WC = w_c , Choked weight flow (lb/sec)

WO = W , Mass flow ($w/(\rho_r u_r r_r^2)$)

Θ_o , Mass flow average total temperature ($\bar{T}_o/T_r$)

Theory

The stream thrust average quantities $\tilde{M}$, $\tilde{\Pi}$, $\tilde{\Pi}_o$ are calculated by subroutine AMFØR. The remaining quantities are given by

$$W = \int PUdA \tag{1}$$

$$\tilde{F}_T = \int \left[\Pi + \gamma M_r^{\ 2} \ \underline{P} U^2 \right] dA \tag{2}$$

$$\Delta\tilde{F}_T = \int \left| \frac{\Pi + \gamma M_r^{\ 2} \ \underline{P} U^2 - \tilde{F}_T / A}{\tilde{F}_T} \right| dA \tag{3}$$

$$\Delta\tilde{\Theta}_o = \frac{1}{W} \int \underline{P} U \frac{\left| \Theta_o - \bar{\Theta}_o \right|}{o} dA \tag{4}$$

$$\Delta\tilde{\Pi}_o = \left(\tilde{\Pi}_o - \tilde{\Pi}_{o1} \right) / \tilde{\Pi}_{o1} \tag{5}$$

$$W_c = g\bar{P}_o \sqrt{\frac{\gamma}{R\bar{T}_o}} \ A \left[\frac{\gamma+1}{2} \right]^{-\frac{\gamma+1}{2(\gamma-1)}} \tag{6}$$

where the "bar" denotes mass flow weighted average conditions

Subroutine BLDGØM

Object

Locate blade centerline in (n,s) coordinates

Options

IØPT2	= 0	No blades in duct
	= 1	Blades in duct

List of Symbols

CØMMØN BLØCK Variables

Theory

This subroutine uses subroutine FLINE to find the centerline in the (n,s) coordinates. Thus the input data from the blade stacking plane is transformed to the duct plane using subroutine TRBLD and stored in the input data line data block BLNE (I,2) used by subroutine FLINE. The output (n,s) coordinates are then stored in the blade data array CØNST(I,L). At the completion of this calculation, the location of the upstream and downstream blade force calculation surfaces are determined by calling subroutine SLETE.

Subroutine BLINE (L,RB1,ZB1,RB2,ZB2)

Object

Calculate neighboring points on output line

Options

None

Variables

L		, Point number
RB1,ZB1 =	$\bar{R}_1,\bar{Z}_1$	, Point at L-1
RB2,ZB2 =	$\bar{R}_2,\bar{Z}_2$	, Point at L

Theory

The points are read from an input table.

Subroutine BLKDAT

Object

Set program constants in BLØCK DATA

Options

None

List of Symbols

ACHI = χ , 0.016 (dimensionless) Clauser constant

AKAPPA = κ , 0.41 (dimensionless) Prandtl constant

APLUS = A^+ , 26.0 (dimensionless) Van Driest constant

CPR = C_{pr} , 5997. (ft^2/sec^2/deg R) Specific heat

CVR = C_{vr} , 4283 (ft^2/sec^2/deg R) Specific heat

EP = e , 2.7182818 (dimensionless)

GAMMA = γ , 1.4 (dimensionless) Ratio of specific heats

GASR = R , 1714. (ft^2/sec^2/deg R) Gas constant

GRAVR = g , 32.2 (ft/sec^2) Acceleration of gravity

PI = π , 3.1415926 (dimensionless)

PRESR = P_r , 2117. (lb^2/ft^2) Reference pressure

PRL = P_{r_L} , 0.72 (dimensionless) Laminar Prandtl number

PRT = P_{r_T} , 0.90 (dimensionless) Turbulent Prandtl number

RHØR = ρ_r , 0.00238 ($slugs/ft^3$) Reference density

SNDR = C_r , 116.0 (ft/sec) Reference speed of sound

TEMPR = T_r , 519.0 (deg R) Reference temperature

TI = t , 0.01745329 (dimensionless)

VISCR = μ_r , 0.37×10^{-6} (slugs/ft/sec) Reference viscosity

Values of Parameter's defined in CØMMØN/PARAM/ are also included for IBM and CDC computer programs.

Subroutine BLKRED (UNIT, RECSIZ, ADDR, BEGREC, NRECS)

Object

Reads NREC 'records' from file 'UNIT' beginning with record BEGREC. NRECS records are stored as a single block, beginning at ADDR. The Univac 1100 library I/O routine NTRAN is used in this subroutine.

Variables

UNIT	=	logical unit#	(Integer)
RECSIZ	=	record size in words	(Integer)
BEGREC	=	first record to read	(Integer)
NRECS	=	# of logical records to read	(Integer)
ADDR	=	beginning address to store the NRECS & RECSIZ records read	

Theory

BLKRED (with entry BLKWRT) was developed to allow NTRAN compatibility with ANSI standard DEFINE FILE I/O operations. In particular, a call to BLKRED with NRECS = 1 is identical to a random access fortran read.

In order to simulate DEFINE FILE I/O, it is necessary for BLKRED to maintain a list of pointers into the various disk files. The pointer list, DSKLOC, is in a common block |UNITS| which must be allocated in a static (root) segment. The location pointer and read size are used to position the disk for I/O access. After the I/O access, the pointer is positioned accordingly.

BLKRED will issue a diagnostic message and cause program termination if either of two abnormal conditions are detected.

1) the record # is negative

2) NTRAN returns on error status less than zero (see UNIVAC FORTRAN V library routine NTRAN description on UNIVAC ASCII FORTRAN routine NTRAN$ description)

Subroutine BLPARM

Object

Calculate boundary layer parameters

Options

NØPT4 = 1 Duct with centerbody

= 2 Duct without centerbody

IØPT11 = 0 Wall boundary OD wall

= 1 Freestream boundary

List of Symbols

BLP(1,I) = $\hat{U}_{s_e}$, Inviscid edge streamwise velocity ($\hat{u}_{s_e}/u_r$)

BLP(2,I) = Π_e , Viscous edge static pressure (P_e/P_r)

BLP(3,I) = Π_{o_e} , Viscous edge total pressure (P_{o_e}/P_r)

BLP(4,I) = Θ_e , Viscous edge static temperature (T_e/T_r)

BLP(5,I) = M_e , Viscous edge Mach number

BLP(6,I) = U_{s_e} , Viscous edge streamwise velocity (u_e/u_r)

BLP(7,I) = $\underline{P}_e$, Viscous edge density (ρ_e/ρ_r)

BLP(8,I) = δ/r_r , Edge of boundary layer

BLP(9,I) = δ^*/r_r , Displacement thickness

BLP(10,I) = θ/r_r , Momentum thickness

BLP(11,I) = H_{12} , Shape factor

BLP(12,I) = R_{e_θ} , Reynolds number ($\rho_e u_e \theta/\mu_e$)

BLP(13,I) = $\hat{\underline{P}}_e$, Inviscid edge density ($\hat{\rho}_e/\rho_r$)

BLP(14,I) = δ_ϕ/r_r , Swirl displacement thickness

BLP(15,I) = θ_ϕ/r_r , Swirl momentum thickness

BLP(16,I) = U_{ϕ_e} , Viscous edge swirl velocity (u_{ϕ_e}/u_r)

BLP(17,I) = $\hat{U}_{\phi_e}$, Inviscid edge swirl velocity $(\hat{u}_{\phi_e}/u_r)$

WS = Ω_s , Viscous streamwise vorticity $(r_r\omega_s/u_r)$

WP = Ω_ϕ , Viscous tangential vorticity $(r_r\omega_\phi/u_r)$

WV = Ω , Viscous total vorticity $(r_r\omega/u_r)$

WSI = $\hat{\Omega}_s$, Inviscid streamwise vorticity $(r_r\hat{\omega}_s/u_r)$

WPI = $\hat{\Omega}_\phi$, Inviscid tangential vorticity $(r_r\hat{\omega}_\phi/u_r)$

WI = $\hat{\Omega}$, Inviscid total vorticity $(r_r,\hat{\omega}/u_r)$

EWP = ε , Vorticity test

g/g_w , Gap/Gap at wall

Theory

For internal flows with thick boundary layers, normal pressure gradients, and swirl; the following boundary layer parameters may be defined.

$$\delta^* = \int_0^\delta \frac{g}{g_w}\left[\frac{\hat{P}\hat{U}_s}{(\hat{P}\hat{U}_s)_e} - \frac{PU_s}{(PU_s)_e}\right] dy \qquad (1)$$

$$\theta = \int_0^\delta \frac{g}{g_w}\left\{\frac{PU_s}{(PU_s)_e}\left[1-\frac{U_s}{U_e}\right] - \frac{\hat{P}\hat{U}_s}{(\hat{P}\hat{U}_s)_e}\left[1-\frac{\hat{U}_s}{\hat{U}_{se}}\right]\right\} dy \qquad (2)$$

$$\delta_\phi = \int_0^\delta \left[\frac{\hat{P}\hat{U}_\phi^2}{(\hat{P}\hat{U}_\phi^2)_e} - \frac{PU_\phi^2}{(PU_\phi^2)_e}\right] dy \qquad (3)$$

$$\theta_\phi = \int_0^\delta \frac{g}{gw} \left\{ \frac{\rho us}{(\rho u_s)_e} \left[1- \frac{u_\phi}{u_{\phi e}}\right] - \frac{\hat{\rho}\hat{u}s}{(\hat{\rho}\hat{u}_s)_e} \left[1- \frac{\hat{u}\phi}{\hat{u}_{\phi e}}\right] \right\} dy \tag{4}$$

The edge of the boundary layer is determined by comparing the viscous and inviscid vorticity distributions where vorticity is given by

$$\omega_\phi = V^2 \frac{\partial}{\partial n} \frac{u_s}{V} \tag{5}$$

$$\omega_s' = \frac{V}{r} \frac{\partial}{\partial n} (ru_\phi) \tag{6}$$

$$\omega' = (\omega_\phi{}^2 + \omega_s{}^2) \tag{7}$$

Then the edge of the boundary layer is defined by

$$\varepsilon = \left| \frac{\omega - \hat{\omega}}{\hat{u}/\delta} \right| = 0.1 \tag{8}$$

FUNCTIØN BPLUSR (AKPULS)

Object

Calculate rough wall integration constant

Options

None

List of Symbols

AKPLUS = K^+ , Roughness Reynolds number (dimensionless)

BPLUSR = $B^{+\prime}$, Law of wall constant (dimensionless)

$U^{+\prime}$, Universal velocity (dimensionless)

$Y^{+\prime}$, Universal distance (dimensionless)

Theory

The law of the wall as shown in Ref. 1 can be written

$$U^+ = \frac{1}{K}\left[\ln y^+ + B^+\right] \tag{1}$$

where for a smooth wall

$$B^+ = 2.05,\ K^+ < 3.33 \tag{2}$$

and for a rough wall

$$B^+ = 3.4 - \ln K^+ \qquad K^+ > 3.33 \tag{3}$$

References

1. Schlicting, H.: Boundary Layer Theory 6th Ed., McGraw Hill Book Co., 1968.

Subroutine CALINV

Object

Calculate inviscid flow field solution.

Options

Calculate flow from J = JFIRS, JLAS
IF (IØPT15.NE.0) JFIRS = IØPT15
IF (IØPT16.NE.0) JLAS = IØPT16
Calculate only for IØPT1 = 3 or 4
NOPT5 $\neq$ 0 Error exit

List of Symbols

Same as CKINPT

BINP(1, K)	$= P_o$	, Total pressure (psf)
BINP(2, K)	$= P$	, Static pressure (psf)
BINP(3, K)	$= \alpha$	, Swirl angle (deg)
BINP(4, K)	$= T_o$	, Total temperature (deg R)
ITERAL	$= \nu_\alpha$	, Swirl angle iteration number
ERRA	$= E_\alpha$	, Local error in swirl angle
ERRAM	$= E_{nd}$	, Maximum error in swirl angle

Theory

Given the swirl angle α, the analysis is identical to subroutine CKINPT. The calculation of the inviscid flow field requires also the solution of the angular momentum equation which is given by

$$(RU_\phi)_K = (R_I U_{\phi I})_K \tag{1}$$

where RU_ϕ is the angular momentum at an arbitrary station and $R_i U_{\phi i}$ is the inlet angular momentum which is given. An outer iteration loop is then programmed to solve Eq. (1) to get the swirl angle α. With α known, the inner iteration loop is the same as subroutine CKINPT. This solution is obtained for each streamwise station J = JFIRS, JLAS.

References

1. Anderson, O. L. and D. E. Edwards: Extensions to an Analysis of Turbulent Swirling Compressible Flow in Axisymmetric Ducts UTRC Report R81-914720-18, February 1981.

Subroutine CASC (ARG. List)

Object

Calculate cascade performance

Options

NØPT5 = 0 continue calculation

> 1 Error - stop calculation

IØPT2 = 2 Not used - predict C_L, C_D

= 3 Predict α_2, Z_B

ISHAPE Blade shape index see input data

List of Symbols

Argument list (see Fig. 1)

ALIND = α_i , Induced angle of attack (deg)

ALPS = α_s , Stagger angle (deg)

ALPI = α_1 , Inlet angle (deg)

ALP2 = α_2 , Exit angle (deg)

AMACH = M , Inlet Mach number

BCHØRD = c , Chord (dimensionless)

CL = C_L , Life coefficient

CD = C_D , Drag coefficient

CX21 = U_{S2}/U_{s1}, Streamwise velocity ratio

GAM = γ , Ratio of specific heats

IØPT2 , Force option

ISHAPE , Shape option

NØPT5 , Error flag

PHIC = ϕ_c , Circular arc camber angle (deg)

RHØCX = $(PU_s)_{2k}/(PU_s)_1$, Mass flow ratio

SØLD = σ , Solidity (dimensionless)

TM = t , Thickness (dimensionless)

WIND = W_i , Induced velocity (dimensionless)

ZLØSS = Z_B , Loss coefficient

C_L Data Correlation (see Fig. 2)

ALPMAX = α_M , $C_L(\alpha_M) = C_{LM}$

ALPO = α_o , $C_L(\alpha_o) = 0$

AMCR = M_{cr} , Critical Mach number

CB = C_B , Design lift coefficient

CBE = C_{Be} , Reference design lift coefficient

CLE = C_{Le} , Reference lift coefficient

CLMAX = C_{LM} , Maximum lift coefficient

CLP = n , Correlation parameter

CLO = C_{LO} , $C_L(0) = C_{LO}$

DCLS = a , Correlation parameter

CDLO = $(dC_L/d\alpha)_o$, Lift curve slope

EPC = ε , Deviation from ideal lift curve slope

PHICE = ϕ_{ce} , Reference camber angle (deg)

C_D Data Correlation (see Fig. 3)

ANG20	$= \alpha_{20}$	, Angle to minimum C_{DO} (deg)
CDBP	$= n_{CBD}$	, Power correlation parameter
CDP	$= n_{CD}$	, Power correlation parameter
CDBO	$= C_{DBO}$	, Minimum drag (loss bucket)
CDO	$= C_{DO}$	, Minimum drag
DANG1	$= \Delta\alpha_2$	, Angle to 2 - C_{DBO}
DANG2	$= \Delta\alpha_1$	, Angle to 2 - C_{DO}
DCBO	$= \Delta C_{DBO}$	, Correlation parameter
DCDO	$= \Delta C_{DO}$	, Correlation parameter

C_L, CD to α_2, Z_B (see Fig. 4)

FS	$= F_s$	, Streamwise force coefficient
FP	$= F_\phi$	, Tangential force coefficient
PO2PO1	$= P_{T2}/P_{T1}$	, Total pressure ratio
P2P1	= P2/P1	, Static pressure ratio
T1	$= T_{T_1}/T_1$	, Temperature ratio
T2	$= T_{T_2}/T_1$	, Temperature ratio
WS	$= W_s$	, Streamwise induced velocity (dimensionless)
WP	$= W_\phi$	, Tangential induced velociy (dimensionless)

Cascade Correlation (see Fig. 5)

AKDELS	$= K_\delta$	, Shape parameter
AMSIG	$= M_\delta$	, Camber parameter
AKDELT	$= K_{\delta t}$	, Thickness parameter
AIOO	$= i_{oo}$	, Incidence angle (deg)

AN	$= n$	, Power
AKIT	$= K_{it}$	, Thickness parameter
AIMO	$= i_{mo}$	, Minimum loss incidence angle (deg)
AINCD	$= i$	, Incidence angle (deg)
B	$= b$	, Power law correlation
D	$= D$	, Diffusion parameter
DELO	$= \delta_o$	, Deviation angle (deg)
DELOO	$= \delta_{oo}$	, Deviation angle $\phi_c = 0$ (deg)
ZLOSM	$= Z_{BM}$	, Minimum loss

Theory

The analysis used in this subroutine is described in detail in Ref. 1. The experimental data correlations for the cascade analysis was obtained from Ref. 2. Experimental data for the back pressure correction was obtained from Ref. 3. The lift and drag coefficient correlation parameters are based on thin airfoil theory described in Ref. 4. Lift and drag data were obtained from Ref. 4. The conversion of lift and drag to exit angle and loss is based on resolution of force vectors. (see Ref. 1). Since the angle of attack must account for induced velocity effects, the concept of momentum induced velocity was introduced (see Ref. 5). This induced velocity can be related to cascade back pressure effects (see Ref. 1).

References

1. Egolf, T. A., O. L. Anderson, D. E. Edwards, and A. J. Landgrebe: An Analysis for High Speed Propellor-Nacelle Aerodynamic Performance Prediction. Vol. 1, Theory and Initial Application. UTRC Report R79-912949-19, NASA Contract NAS3-20961, June 1979.

2. Johnson, I. A. and R. O. Bullock: Aerodynamic Design of Axial Flow Compressors. NASA SP-36, 1965.

3. Mensing, A. E.: Investigation of the Effect of Back Pressure on Cascade Performance. UTRC Report R-0837-2, 1960.

4. Abbot, I. H. and A. E. Von Doenhoff: Theory of Wing Sections, Dover Publications, 1959.

5. McCormick, B. W.: Aerodynamics of VSTOL Flight, Academic Press, New York, 1967.

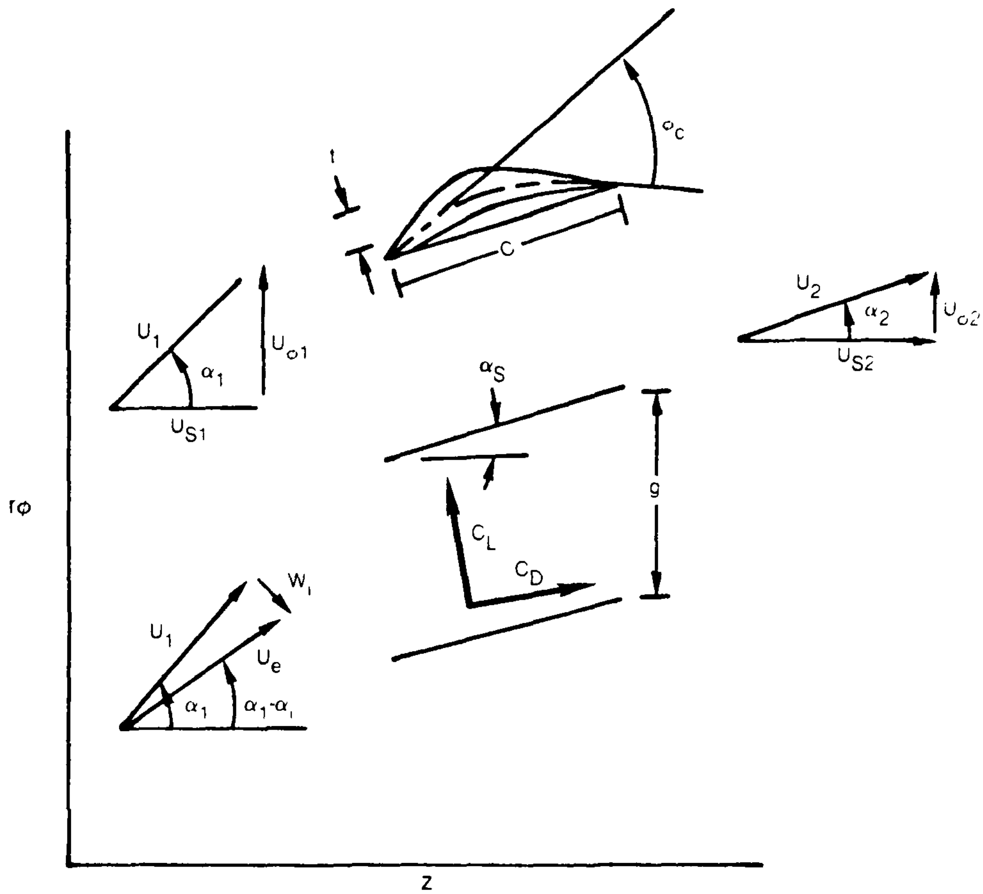


Fig. 1. Argument List Variables for Cascade Parameters

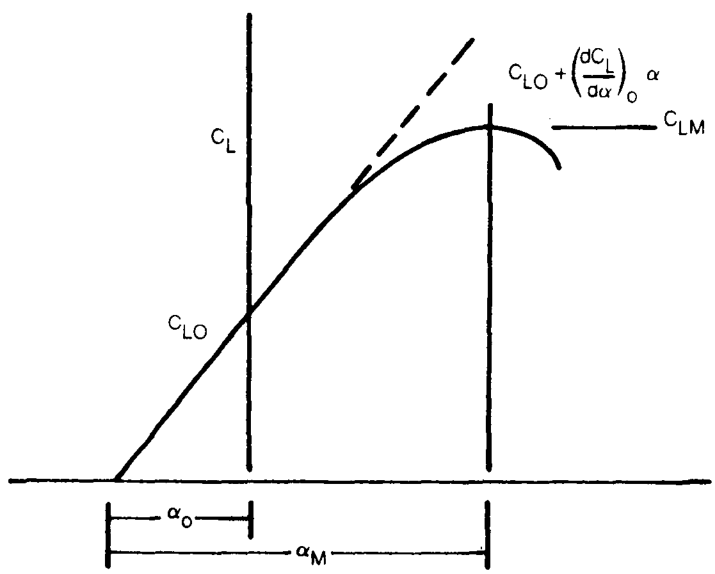


Fig. 2. C_L Data Correlation Parameters

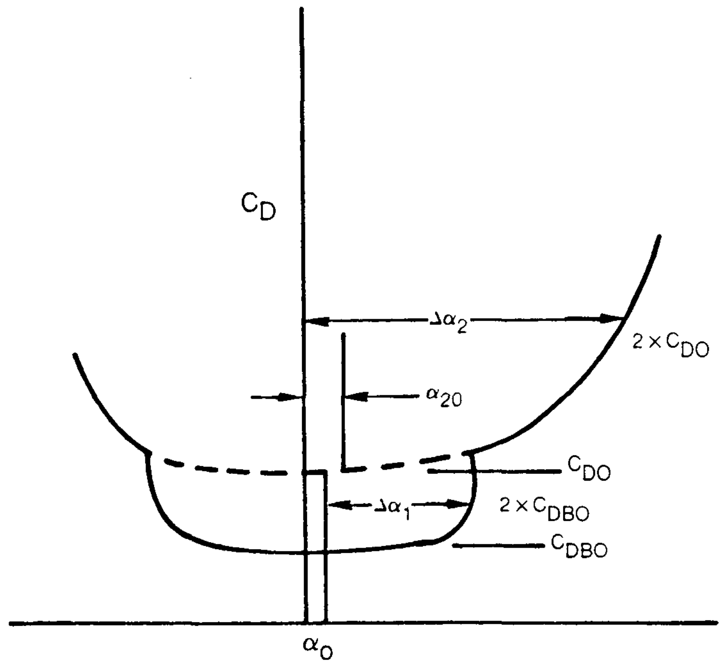


Fig. 3. C_D Data Correlation Parmeters

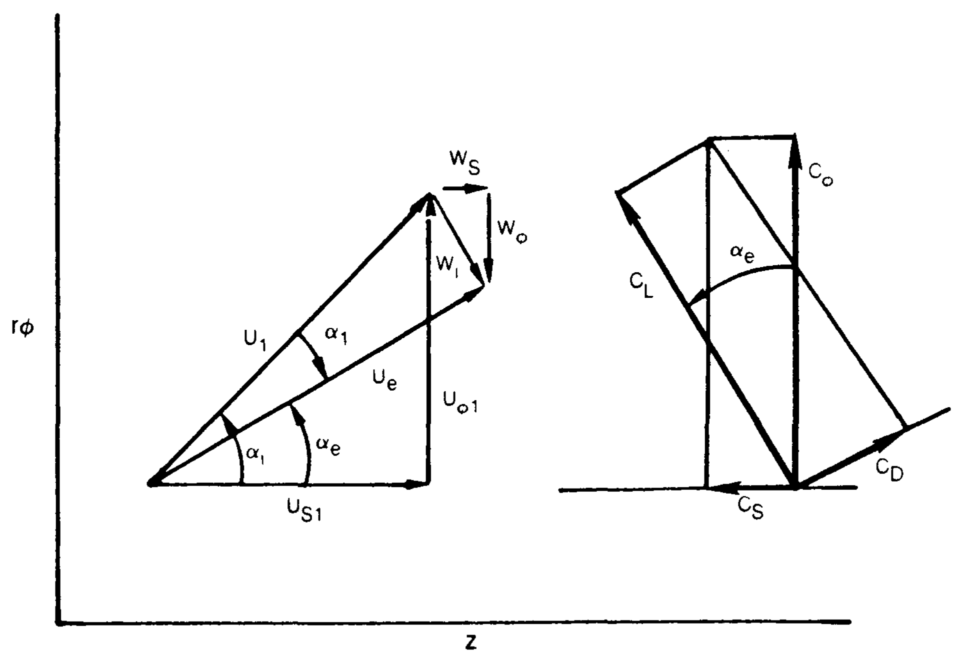


Fig. 4. Resolution of Force Vectors

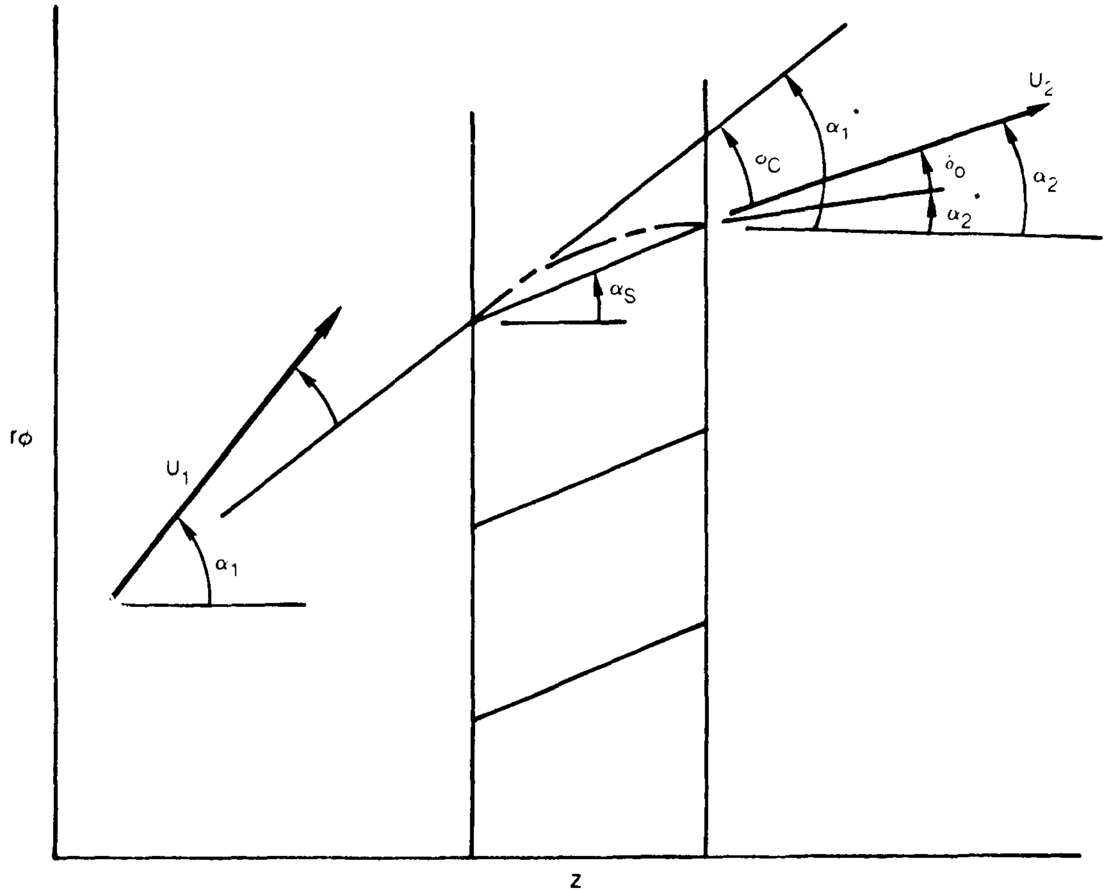


Fig. 5. Cascade Correlation Parameters

Function CDS (DDS, DETA)

Object

Calculate Roberts' mesh distortion parameter

Options

None

Input Variables

DDS	=		Ratio of mesh distortion at wall $\Delta\eta/\Delta n$
DETA	=	$\Delta\eta$,	Mesh size at boundary - uniform mesh
		Δn ,	Distorted mesh size at wall

Output Variables

CDS	c ,	Roberts' mesh parameter

Theory

Let $$c = 1/2 + \epsilon \tag{1}$$

Then Roberts' transformation can be written

$$\phi = \left(\frac{1+\epsilon}{\epsilon}\right)^{(2\Delta\eta-1)} \tag{2}$$

$$\Delta n = \frac{(1+\epsilon)\phi - \epsilon}{1+\phi} \tag{3}$$

$$\Delta n = \Delta\eta/DDS \tag{4}$$

Eq. (2) through (4) can be solved iteratively for ε as follows:

$$\epsilon = 0 \tag{5}$$

$$\phi = \frac{\Delta n + \epsilon}{1+\epsilon-\Delta n} \tag{6}$$

$$\epsilon = \left[\phi^{\frac{1}{2\Delta\eta-1}} - 1\right]^{-1} \tag{7}$$

Convergence occurs when

$$\left| \frac{\epsilon^{\nu+1} - \epsilon^{\nu}}{\epsilon^{\nu}} \right| < 1E-04 \qquad (8)$$

Function CFCØLE (DEL, DSTR, H12, RET)

Object

Calculate Coles' wall friction coefficient

Options

None

List of Symbols

AKAP	$= \kappa$	, Von Karmen constant (.41)
BPLUS	$= B^+$	, Constant of integration (2.05)
CFCØLE	$= C_f$	, Friction coefficient
DEL	$= \delta$	, Boundary layer thickness (dimensionless)
DSTR	$= \delta^*$	, Displacement thickness (dimensionless)
H12	$= H_{12}$	, Shape factor
RET	$= R_{e\theta}$	, Reynolds number
UIUS	$= U_\infty/U^*$	, Velocity ratio

Theory

Coles' skin friction law, Ref. 1, can be written

$$\sqrt{\frac{2}{C_f}} = \frac{U_\infty}{U^*} = \frac{\left\{\ln\left[\frac{U^*}{U_\infty} \frac{\delta}{\delta^*} H_{12} Re_\theta\right] + B^+ - 2.0\right\}}{\left[1 - 2\frac{\delta}{\delta^*}\right]} \tag{1}$$

Eq. (1) can be solved for U_∞/U^* by successive substitution.

References

1. Coles, D. E.: The Turbulent Boundary Layer in a Compressible Fluid, Rand Report R-403-PR, 1962.

Subroutine CKINPT

Object

Check input data for radial equilibrium

Options

IØPT1	$\neq 4$	Do not calculate
NØPT5	$\neq 0$	Error exit
IØPT5	= 2	FØRCE data equals FLØWIN data
IJ	= 1	Inlet flow data
IB	= 2	Force data
INEX	= 1	Upstream data
INEX	= 2	Downstream data
IDBG13	= 1	Debug printout
WFLØW	= 0	Static pressure check only
WFLØW	> 0	Pressure check and weight flow iteration

List of Symbols

ERR	$= \varepsilon$	, Error in interaction
EPS	$= \varepsilon_o$	, Minimum error
FG(2, K)	$= \phi(2)$	, Equation 4
FG(4, K)	$= \phi(2)$	, Equation 5
ITER	$= \nu$	, Iteration number
PHMAX		, Maximum pressure possible (psfa)
PS11, PS12	$= \psi_1^\nu, \psi_2^\nu$	, Upper and lower bound air stream function (dimensionless)
WF	$= W^\nu$	, Weight flow v^{th} iteration (lb/sec)

WFLØW	$= W$	, Input weight flow (lb/sec)
WMAX	$= W_{max}$	, Maximum weight flow possible (lb/sec)
WMIN	$= W_{min}$	, Minimum weight flow possible (lb/sec)
XL	$= X_L$	, Lower bound on X (dimensionless)
XM	$= X_M$	, X for choked flow (dimensionless)
XU	$= X_U$	, Upper bound on X (dimensionless)
X1	$= X_1^{\nu}, X_2^{\nu}$	, Iterative values for X (dimensionless)
PSIHT,PSIT	$= \psi_H, \psi_T^{\nu}$	, Value of stream function (dimensionless)

Theory

Input data for the total pressure, static pressure, swirl angle, and total temperature must satisfy the continuity equation, and the radial momentum equation. If these equations are not satisfied, the static pressure is adjusted. The solution of these equations can be obtained by a transformation of variables. Let

$$X = \left(\frac{\Pi}{\Pi_0}\right)^{\frac{\gamma-1}{\gamma}} \tag{1}$$

and

$$a(\eta) = 2\left\{-\frac{1}{Xv}\frac{\partial V}{\partial n}\cos^2\alpha + \frac{1}{XR}\frac{\partial R}{\partial n}\sin^2\alpha\right\} \tag{2}$$

and then the radial momentum equation becomes

$$\frac{dX}{dt} + \left[a(\eta) + \frac{\gamma-1}{\gamma}\frac{d}{d\eta}(\ln \Pi_0)\right] X = a(\eta) \tag{3}$$

which is an ordinary first order "linear" equation. The solution is given by

$$\phi(\eta) = \exp\left\{\int_0^{\eta} a(Y)\,dY + \frac{\gamma-1}{\gamma}\ln\left(\frac{\Pi_0}{\Pi_{OH}}\right)\right\} \tag{4}$$

$$\Phi(\eta) = \int_0^{\eta} a(Y)\,\phi(Y)\,dY \tag{5}$$

$$X = (X_0 + \Phi(\eta)) / \phi(\eta) \tag{6}$$

where X_0 is the hub static pressure ratio. The continuity equation becomes

$$\frac{d\Psi}{d\eta} = \frac{\Pi_0 G \cos\alpha}{M_r V\sqrt{\Theta_0}} X^{\frac{1}{\gamma-1}} (1-X)^{1/2} \tag{7}$$

and

$$w(\eta) = 2\pi \rho_r c_r r_r^2 g \Psi(\eta) \tag{8}$$

The constant X_0 is determined by the boundary condition

$$w(1) = w \tag{9}$$

using an iteration scheme described below.

First let us examine the function

$$f(X) = X^{\frac{1}{\gamma-1}} (1-X)^{1/2} \tag{10}$$

f(X) has a maximum at

$$X = X_m = \frac{2}{\gamma+1} \tag{11}$$

Hence from Eq. (1)

$$\frac{\Pi_M}{\Pi_0} = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} \tag{12}$$

Equation (12) is precisely the condition for choked flow when M = 1. Substitution of Eq. (12) into Eq. (10) yields an a-priori condition for the maximum weight flow possible (i.e., the choked flow condition). For a subsonic solution we have the condition

$$\frac{2}{\gamma+1} < X < 1 \tag{13}$$

Furthermore, it is noted that we can find a-priori X_0 such that

$$\begin{aligned} &\frac{2}{\gamma+1} < X_L < X_0 < X_U < 1 \\ &f(X_L) < f(X_M) \\ &f(X_0) > 0 \end{aligned} \tag{14}$$

by substituting Eq. (6) into Eq. (10). Thus X_L and X_U are the bounds for choosing subsonic solutions with no reverse flow. The iteration scheme then consists of narrowing the bounds of X_L and X_U until convergence occurs. This procedure is illustrated in Fig. 17.

$$X^{\nu+1} = X_1^{\nu} + \frac{\Psi - \Psi_1^{\nu}}{\Psi_2^{\nu} - \Psi_1^{\nu}} \left(X_2^{\nu} - X_1^{\nu} \right) \tag{15}$$

$$\begin{aligned} &\text{If } (\Psi^{\nu+1} < \Psi)\ X_1^{\nu} = X^{\nu} ;\ \Psi_1^{\nu} = \Psi \\ &\text{If } (\Psi^{\nu+1} > \Psi)\ X_2^{\nu} = X^{\nu} ;\ \Psi_2^{\nu} = \Psi \end{aligned} \tag{16}$$

and ψ^{ν} is obtained by integrating Eq. (7) with $X_o = X^{\nu+1}$ substituted into Eq. (6). Convergence occurs when

$$|X^{\nu+1} - X^{\nu}| < \epsilon_0 \tag{17}$$

Once X is known, the static pressure is obtained from (1) and substituted for the input static pressure.

References

1. Anderson, O. L. and D. E. Edwards: Extensions to an Analysis of Turbulent Swirling Compressible Flow in Axisymmetric Ducts. UTRC Report R81-914720-18, 1981.

Subroutine CLINE (JJ, KK, RB, ZB, SB, ANB, XB)

Object

Calculate $(\bar{n},\bar{s})$ coordinates for point $(\bar{R},\bar{Z})$

Options

None

List of Symbols

J_1K		, Corner point on grid
RB, ZB	$= \bar{R},\bar{Z}$	, Dependent coordinates (dimensionless)
SB, ANB	$= \bar{s},\bar{n}$	, Independent coordinates (dimensionless)
XB	$= \bar{X}$	, Distance from inlet (dimensionless)

Theory

For a first order expansion we have

$$\bar{R} = R_{J,K} + \frac{1}{2}\left[R_{J+1,K} + R_{J+1,K+1} - R_{J,K} - R_{J,K+1}\right]\frac{(\bar{S}-S_{J,K})}{\Delta S} + \frac{1}{2}\left[R_{J,K+1} + R_{J+1,K+1} - R_{J,K} - R_{J+1,K}\right]\frac{\bar{n}-n_{J,K}}{\Delta n} \quad (1)$$

$$\bar{Z} = Z_{J,K} + \frac{1}{2}\left[Z_{J+1,K} + Z_{J+1,K+1} - Z_{J,K} - Z_{J,K+1}\right]\frac{(\bar{S}-S_{J,K})}{\Delta S} + \frac{1}{2}\left[Z_{J,K+1} + Z_{J+1,K+1} - Z_{J,K} - Z_{J+1,K}\right]\frac{(\bar{n}-n_{J,K})}{\Delta n} \quad (2)$$

These two equations can be solved for $\bar{s},\bar{n}$ and $\bar{X}$ may be obtained by interpolation.

Subroutine CØØR(JS,KS)

Object

Interpolates coordinates in streamwise direction.

Options

IØPT9=0 Computes approximate coordinates
IØPT9≠0 Coordinates stored on drum

List of Symbols

DSTEP	$= \Delta S$	, Streamwise step size (dimensionless)
DX	$= \Delta X$	, Interpolation between JS and JS-1 stations
DXNEXT	$= \Delta X_N$	, Interpolation for next step
JDRUM	=	, Drum unit number
JS	=	, JS^{th} station stored on drum
KS	=	, KS^{th} station interpolated between JS
ZHUB	$= Z_H$	, Axial station hub (dimensionless)
ZNEXT	$= Z_N$	, Next axial station (dimensionless)
ZTIP	$= Z_T$	, Axial station tip (dimensionless)

Theory

Let the streamwise coordinate S be given by

$$S = \Delta S(JS-1) + dS \cdot (KS-1) \tag{1}$$

where

$$\Delta S = S_L/(JLAST-1) \tag{2}$$

$$dS = \Delta S/KDS \tag{3}$$

Then if station 1 is at JS-1 and station 2 at JS, a simple linear interpolation of the coordinates may be made from those stored on the drum. ZNEXT is the axial location of the KS+1 station.

Subroutine CØØRST

Object

Controls flow for coordinate calculation

Options

IØPT13=0 No slots in duct
=1 Slots in duct

IØPT14=0 ten streamlines are calculated
>0 IØPT14 streamlines are calculated

List of Symbols

DSTEP	= ΔS = DS	, Streamwise step size (dimensionless)
DX	= $\Delta\eta$	, Normal coordinate step size (dimensionless)
DY1	= δY	, First derivative (dimensionless)
DY2	= $\delta^2 Y$	, Second derivative (dimensionless)
ICK	= 0,1	, Flag; no overlap, overlap
II	= 1,2	, Flag; start integration, continue integration
ISLT1, ISLT2	=	, First slot number, second slot number
IW1,IW2	=	, First slot wall, second slot wall
JCØUNT	=	, Streamwise station counter
KLHØLD	=	, Number of streamlines to interpolate
KN	=	, Number of streamlines to integrate
MSLØT	=	, Slot counter
NSLØT	=	, Total number of slots
RA(I,J)	= R(I,1,J)	, Temporary storage for wall coorindate
X	= **X**	, Normal coordinate (dimensionless)

XM	$= X$	, Interpolation distance (dimensionless)
X2	$= X_2$	, Midpoint of three point difference (dimensionless)
Y	$= Y$	, Function to be interpolated (dimensionless)
Y1	$= Y(X_r)=Y_1$	, Known values of Y (dimensionless)
Y2	$= Y(X_2)=Y_2$	, Known values of Y (dimensionless)
Y3	$= Y(X_3)=Y_3$	, Known values of Y (dimensionless)
Z	$= Z$	, Axial distance (dimensionless)
ZZ1,ZZ2	$= Z_1,\ Z_2$	, Location of adjacent slots (dimensionless)

Theory

This subroutine controls the calculation flow for the coordinates according to flow chart Fig. 6. The basic calculation scheme with slots is to calculate the streamlines through successively larger ducts and storing only those coordinates satisfying the condition $(Z_1 \leq Z \leq Z_2)$ as shown in Fig. 7.

In addition, it was determined that only KN streamlines need be calculated by integration, the remainder up to KL streamlines may be calculated using a linear interpolation.

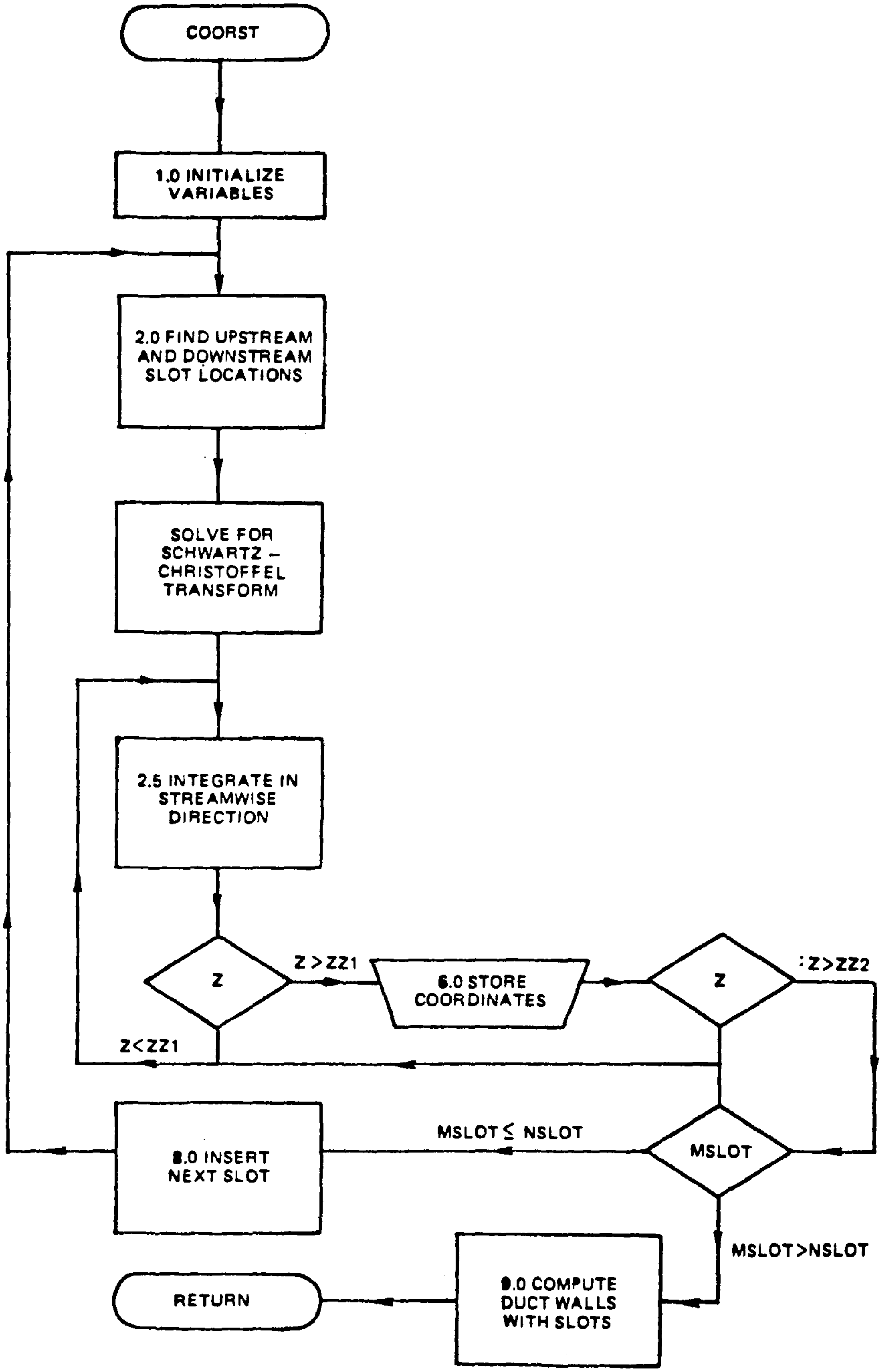


FIG. 6. FLOW CHART FOR SUBROUTINE COORST

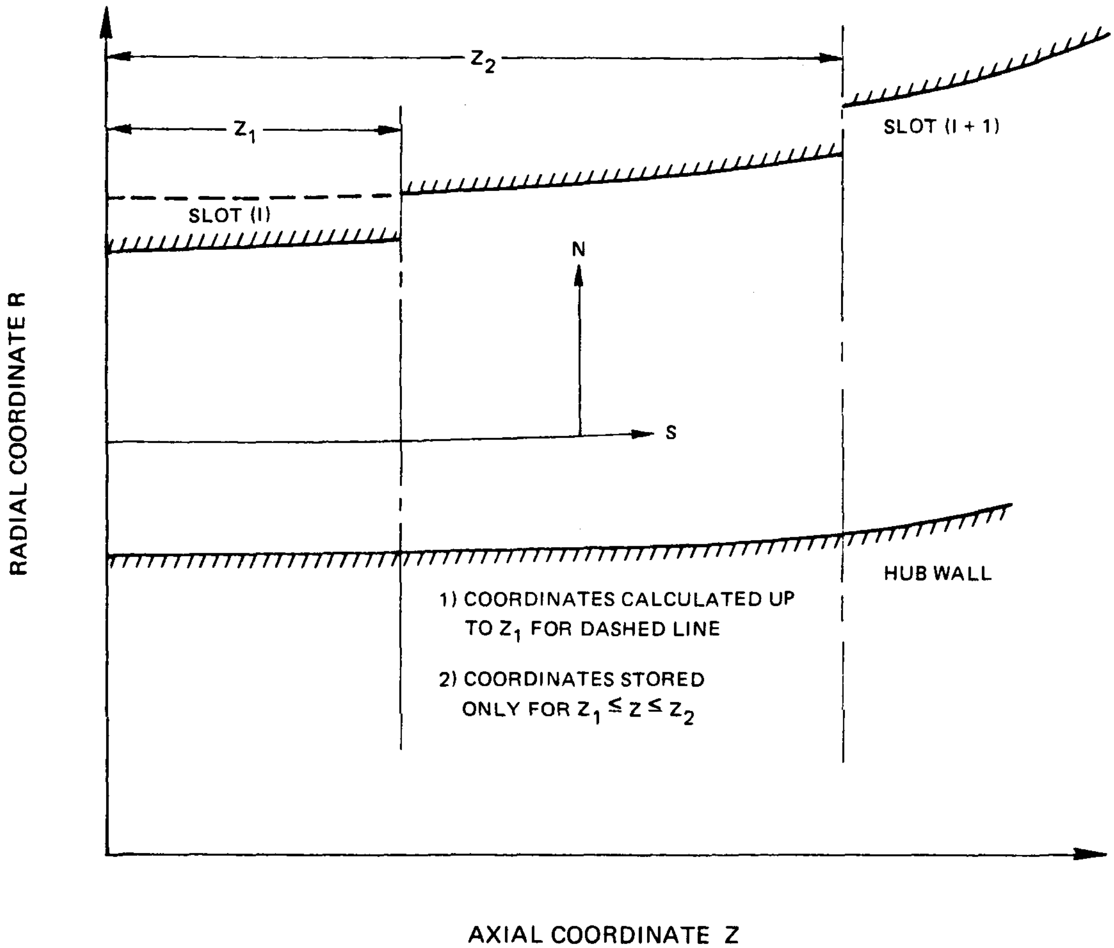


FIG. 7. CALCULATING DUCTS WITH SLOTS

Subroutine CØØR1(KSS,JSS)

Object

Complete approximate coordinate functions.

Option

NØPT3	= 1	Construct coordinate
	= 2	Calculate coordinates at KSS, JSS

List of Symbols

RØ(1,K)	= R	, Radius (dimensionless)
RØ(2,K)	= dR/dZ	, Derivative of radius (dimensionless)
RØ(3,K)	= d^2R/dZ^2	, Second derivative of radius (dimensionless)
RØ(4,K)	= Z	, Axial distance (dimensionless)
RØ(5,K)	= V	, Metric scale coefficient (dimensionless)
RØ(6,K)	= dV/dS	, Derivative of metric scale coefficient (dimensionless)
RØ(7,K)	= Y_T	, Distance across duct (dimensionless)
RØ(8,K)	= S	, Streamwise coordinate (dimensionless)
RØ(9,K)	= $\mathring{m}$	, Mass flow bleed (dimensionless)
RØ(10,K)	= $_w$	, Wall temperature (dimensionless)

RØS(I) RO(I,K)

Note: Three arrays defined where ϕ takes on the value H, M, T

ϕ = H, Hub wall

= M, Mean line

= T, Tip wall

KSS	, Coarse grid station
JSS	, Fine grid station

Theory

The approximate coordinates are calculated by geometric construction using the relations derived in Ref. 1. These approximate coordinates are used as a first guess by subroutine CØØR4.

References

1. Anderson, O. L.: User's Manual for a Finite Difference Calculation of Turbulent Swirling Flow in Axisymmetric Ducts with Slot Cooled Walls. Vols. 1 & 2. USAAMRDL-TR-74-50, 1974.

Subroutine CØØR2

Object

Calculate wall curvature and arc length

Options

None

Variables

RM(1,J)	R_{HI}	,Radius ID wall (dimensionless)
RM(2,J)	Z_{HI}	,Axial length ID wall (dimensionless)
RM(3,J)	X_{HI}	,Arc length ID wall (dimensionless)
RM(4,J)	K_{HI}	,Curvature ID wall (dimensionless)
RM(5,J)	R_{T_I}	,Radius OD wall (dimensionless)
RM(6,J)	Z_{TI}	,Axial length OD wall (dimensionless)
RM(7,J)	X_{TI}	,Arc length OD wall (dimensionless)
RM(8,J)	K_{TI}	,Curvature OD wall (dimensionless)
RM(9,J)		
RM(10,J)		

Theory

The arc length is given by

$$dx_J = \sqrt{(dR)_J^2 + (dZ)_J^2} \tag{1}$$

$$x_J = \int_0^J dx_J \tag{2}$$

where

$$(dR)_j = R_{j+1} - R_j \tag{3}$$

$$(dZ)_j = Z_{j+1} - Z_j$$

and the curvature is given by

$$K = \frac{\frac{dZ}{dx}\frac{d^2R}{dx^2} - \frac{dR}{dx}\frac{d^2Z}{dx^2}}{\left[\left(\frac{dZ}{dx}\right)^2 + \left(\frac{dR}{dx}\right)^2\right]^{3/2}} \tag{4}$$

where the derivatives are obtained using a central difference formula.

Subroutine CØØR3(KSS,JSS)

Object

Compute Coordinate Functions

Options

LØP=1 Compute initial constants
=2 Integrate one step
=3 Do not integrate

List of Symbols

AO	$= A_o$	, Inlet height W plane (dimensionless)
ALO	$= \alpha_o$	, Inlet angle W plane (dimensionless)
ANO	$= n_o$	, Inlet height Z plane (dimensionless)
SLO	$= S_L{}^o$	, Initial coordinate length (dimensionless)
RO	$= r_o$	, Inlet radius Z plane (dimensionless)
VO	$= v_o$	, Inlet metric scale coefficient (dimensionless)
SO	$= s_o'$	, Inlet streamwise coordinate (dimensionless)
XBO	$= \tilde{x}_o$	, Real part of C_1 (dimensionless)
YBO	$= \tilde{y}_o$	, Imaginary part of C_1 (dimensionless)
ZETAO	$= \xi_o$	, Constant of integration real (dimensionless)
ETAO	$= \eta_o$	, Constant of integration imaginary (dimensionless)

Theory

The Schwartz-Christoffel transformation (Ref. 1) is integrated along streamlines to get R,Z,V,S,N once the location of the poles are known.

References

1. Anderson, O. L.: User's Manual for a Finite Difference Calculation of Turbulent Swirling Flow in Axisymmetric Ducts with Slot Cooled Walls. Vols. 1 & 2, USAAMRDL-TR-74-50, 1974.

Subroutine CØØR4

Object

Find Schwartz-Christoffel Parameters

Options

None

List of Symbols

AX(1,J)	$= X_H$	, Distance along hub wall (dimensionless)
AX(2,J)	$= X_T$	, Distance along tip wall (dimensionless)
AX(3,J)	$= \alpha_H$	, Wall angle hub (deg)
AX(4,J)	$= \alpha_T$	, Wall angle tip (deg)
AY(1,I,J)	$= S_H^\nu$	, Streamwise coordinate hub (dimensionless)
AY(2,I,J)	$= X_H^\nu$	, Distance along hub wall (dimensionless)
AY(3,I,J)	$= V_H^\nu$	, Metric scale coefficient hub (dimensionless)
AY(4,I,J)	$= R_H^\nu$	, Radius hub (dimensionless)
AY(5,I,J)	$= S_T^\nu$	, Streamwise coordinate tip (dimensionless)
AY(6,I,J)	$= X_T^\nu$	, Distance along tip wall (dimensionless)
AY(7,I,J)	$= V_T^\nu$	, Metric scale coefficient tip (dimensionless)
AY(8,I,J)	$= R_T^\nu$	, Radius tip (dimensionless)
AERR(1,J)	$= S_H^{\nu+1} - S_H^\nu$	, Error in S_H (dimensionless)
AERR(2,J)	$= S_T^{\nu+1} - S_T^\nu$	, Error in S_T (dimensionless)
AO	$= h_o$	, Inlet height W plane (dimensionless)
ALO	$= \alpha_o$	, Inlet angle W plane (dimensionless
ANO	$= n_o$	, Inlet height Z plane (dimensionless)
SLO	$= S_L^o$	, Initial guess of coordinate length (dimensionless)

RO	$= r_o$	, Inlet radius in Z plane (dimensionless)
VO	$= V_o$	, Inlet metric scale coefficient (dimensionless)
SO	$= S_o$	, Inlet streamwise coordinate (dimensionless)
XBO	$= \tilde{X}_o$	, Real part of constant C_1 (dimensionless)
YBO	$= \tilde{Y}_o$	, Imaginary part of constant C_1 (dimensionless)
ZETAO	$= \xi_o$	, Constant of integration (real)(dimensionless)
ETAO	$= \eta_o$	, Constant of integration (imaginary)(dimensionless)

Theory

This subroutine solves for the location of the poles in the Schwartz-Christoffel transformation using the method described in Ref. (1) and (2). The following procedure is used:

1. Construct a table of arc length along the walls and wall to each of the JL input points.

2. An initial guess is made for the location of the poles using the approximate solution from subroutine CØØR1.

3. The Schwartz-Chrisotffel transformation is integrated along the walls to obtain arc length along the wall to each pole.

4. A new guess for the location of the poles is made by comparing arc length.

References

1. Anderson, O. L.: Calculation of Internal Viscous Flows in Axisymmetric Ducts at Moderate to High Reynolds Numbers, Int. J. of Computer and Fluids, Vol. 8, No. 4, December 1980. P. 391-411.

2. Anderson, O. L.: User's Manual for a Finite Difference Calculation of Turbulent Swirling Flows in Axisymmetric Ducts with Slot Cooled Walls. Vols. I & II, USAAMRDL-TR-74-50, 1974.

Subroutine CØØP5 (XH, XT, CURVH, CURVT)

Object

Interpolate wall curvature at Station S

Options

None

Variables

XH	$X_H(S)$	,	Arc length ID wall (dimensionless)
XT	$X_T(S)$	,	Arc length OD wall (dimensionless)
CURVH	$K_H(S)$	,	Curvature ID wall (dimensionless)
CURVT	$K_T(S)$	,	Curvature OD wall (dimensionless)
RM(3,J)	$X_{HI}(J)$	,	Table of X_H (dimensionless)
RM(4,J)	$K_{HI}(J)$	,	Table of K_H (dimensionless)
RM(7,J)	$X_{TI}(J)$	,	Table of X_T (dimensionless)
RM(8,J)	$K_{TI}(J)$	,	Table of K_T (dimensionless)

Theory

The values of $X_H(S)$ and $X_T(S)$ are input. Then the tables are searched and the values of $K_H(S)$, $K_T(S)$ are calculated by linear interpolation.

Subroutine CPLX1(X1,Y1,XB1,YB1,N1,N2,LØP)

Object

Evaluates real and imaginary parts, Schwartz-Christoffel transformation

Options

LØP=1 $W_Z = \tilde{X} + i\tilde{y} = dW/dZ$

=2 $W_{ZZ} = \tilde{X} + i\tilde{y} = d^2W/dZ^2$

List of Symbols

N1	$= N_1$	, Product index
N2	$= N_2$	, Product index
N3	$= N_1+1$	, Product index
X1	$= X$	, X coordinate in Z plane (dimensionless)
Y1	$= Y$	, Y coordinate in Z plane (dimensionless)
XB1	$= \tilde{X}$	, X coordinate in W_Z plane or W_{ZZ} plane (dimensionless)
YB1	$= \tilde{Y}$	, Y coordinate in W_Z plane or W_{ZZ} plane (dimensionless)

Theory

This subroutine evaluates the real and imaginary parts of the Schwartz-Christoffel transformation.

Subroutine CRØSS1(X1,Y1,X2,X2,XB1,YB1,XB2,YB2,S,T)

Object

Find intersection of two straight lines

Options

If $0 \leq s \leq 1.0$ lines cross within points on line A
If $0 \leq t \leq 1.0$ lines cross within points on line B

List of Symbols

(X1,Y1), (X2,Y2)	$= (X_1,Y_1),(X_2,Y_2)$	, Pair of points line A (dimensionless)
(XB1,YB1),(XB2,YB2)	$= (\bar{X}_1,\bar{Y}_1),(\bar{X}_2,\bar{Y}_2)$	, Pair of points line B (dimensionless)
S	$= s$	, Parameter line A (dimensionless)
T	$= t$	, Parameter line B (dimensionless)

Theory

The equations for the two straight lines can be written in parametric form

$$\begin{aligned} X &= (X_2 - X_1)\cdot s + X_1 \\ Y &= (Y_2 - Y_1)\cdot s + Y_1 \\ \bar{X} &= (\bar{X}_2 - \bar{X}_1)\cdot t + \bar{X}_1 \\ \bar{Y} &= (\bar{Y}_2 - \bar{Y}_1)\cdot t + \bar{Y}_1 \end{aligned} \tag{1}$$

These equations can be solved at the point of intersection for s and t. Then if

$$0 \leq s \leq 1 \tag{2}$$

line B crosses line A between the pair of points on line A. If

$$0 \leq t \leq 1 \tag{3}$$

then line A crosses line B within the pair of points on line B.

Subroutine CRØSS2(K,MØLD,RB1,ZR1,RB2,ZB2,SX,TX,MNEW)

Object

Search around coordinate rectangle for crossing point.

Options

If M = MØLD	Skip check for crossing point
$0 \leq ss \leq 1$	lines cross within points on line A
$0 < TT < 1$	lines cross within points on line B

List of Symbols

J,K		, Corner point on grid rectangle
MNEW, MØLD		, New, old crossing side
R1,Z1,R2,Z2	$= R_1,Z_1,R_2,Z_2$	, Points on line A - coordinate grid (dimensionless)
RB1,ZB1,RB2,ZB2	$= \bar{R}_1,\bar{Z}_1,\bar{R}_2,\bar{Z}_2$	, Points on line B (dimensionless)
RX,ZX	$= R_x,Z_x$	, Coordinates for intersection (dimensionless)
SS,TT	$= S,T$	, Parametric coordinates for lines A and B
SX,TX	$= S_x,T_x$	, Parametric coordinates for intersection

Theory

This subroutine searches around the coordinate rectangle for the intersection of line B.

Subroutine DEFFIL

Object

Define random access data files

Options

None

Theory

This subroutine is used only by the IBM version of the ADD code to define random access data files using ANSI standard DEFINE FILE I/O. Details of the data files are described in Section 5.5 of the Manual.

Subroutine DLINE(L,SB1,ANB1,XB1,JB1,KB1)

Object

Store coordinates of output data line

Options

None

Variables

JB1,KB1	Index of corner point
L	Index of input data point
SB1,ANB1 = s_1, n_1	Coordinates of input data point
XB1 = x_1	Distance from inlet of input data point

Theory

This subroutine stores coordinates of input data line at the point L.

Function DROBRT (C, ETA, LØP)

Object

Compute derivative of Roberts' transformation

Options

LØP = 0 wall - wall boundary
LØP = 1 wall-freestream boundary
LØP = -1 freestream-wall boundary

Input Variables

C	= C	,	Distortion parameter
ETA	= η	,	Input variable
LØP		,	Option

Output Variable

DROBRT = $\partial\eta/\partial\eta$, Output variable

Theory

The transform of the Roberts' Stretching for a distorted mesh is given by

$$\frac{\partial\eta}{\partial n} = \left[4\ c\ \ln\left(\frac{c+1/2}{c-1/2}\right)\frac{\phi}{(1+\phi)^2}\right]^{-1} \tag{1}$$

$$\phi = \exp\left[2\ \ln\left(\frac{c+1/2}{c-1/2}\right)\left(\eta' - 1/2\right)\right] \tag{2}$$

where the options are

$$\left.\begin{matrix}\eta' = \eta \\ n = n'\end{matrix}\right\} L\phi P = 0 \qquad \left.\begin{matrix}\eta' = \eta/2 \\ n = 2n'\end{matrix}\right\} L\phi P = 1 \qquad \left.\begin{matrix}\eta' = (1+\eta)/2 \\ n = 2n' - 1\end{matrix}\right\} L\phi P = -1$$

We note that

$$0 \le \eta' \le 1.0 \qquad 0 \le n' \le 1.0 \tag{3}$$

Subroutine DUMIØ (Arg. List)

Object

Read/write to random access data files

Options

IØTYPE = 1	Write to file
IØTYPE = 2	Read from File

Argument List

IØTYPE	Read/write option
UNIT	Logical unit number
RECSIZ	Record size in words
ADDR	Beginning address
JREC	Number of logical records
STATUS	Switch indicating completion of I/O

Theory

This subroutine reads or writes data blocks to random access files and is called only by subroutine BLKRED. It is used only in the IBM version of the ADD code as a transition between UNIVAC NTRAN I/O and ANSI standard DEFINE FILE I/O.

Subroutine ECØINP

Object

Write input data

Options

None

Variables

See subroutine REDINP

Theory

This subroutine prints and labels the input data according to the output format described in Section 4.3.

Subroutine ELINE (TTT,SXT,XXT,TTH,SXH,XXH)

Object

Extrapolate for end points on output data line

Options

None

List of Symbols

SXH, SXT	$= S_H, S_T$	, Streamwise coordinate ID and OD walls
TTH, TTT	$= T_H, T_T$	, Parametric variable ID and OD walls
XXH, XXT	$= X_H, X_T$	, Arc length ID and OD walls (dimensionless)

Theory

The parametric variable T interpolates along the input data line such that

$$T_H = \frac{S_H - \bar{S}_1}{\bar{S}_2 - \bar{S}_1} = \frac{X_H - \bar{X}_1}{\bar{X}_2 - \bar{X}_1} \tag{1}$$

$$T_T = \frac{S_T - \bar{S}_{LLAST-1}}{\bar{S}_{LLAST} - \bar{S}_{LLAST-1}} = \frac{X_T - \bar{X}_{LLAST-1}}{\bar{X}_{LLAST} - \bar{X}_{LLAST-1}} \tag{2}$$

Since T_H, X_H, S_H, $\bar{S}_{z1}$, $\bar{X}_2$ are known, $\bar{S}_1$ and $\bar{X}_1$ may be determined from Eq. (1). Likewise, S_{LLAST}, X_{LLAST} may be determined from Eq. (2).

Subroutine ERPIN (II)

Object

Check error in normal pressure gradient

Options

II = 1	Initial plane
II = 2	J-1 plane
II = 3	J plane

Theory

This subroutine integrates the normal momentum equation at the IIth plane to obtain the static pressure difference OD wall pressure minus ID wall pressure. This static pressure difference is compared to the input static pressure difference. If the difference between calculated and input static pressure difference is greater than one percent returns DIAGNOSTIC NO. 09 and the calculated static pressure difference required to correct the input data.

Subroutine EWLØSS (Arg. List)

Object

Calculate end wall loss

Options

None

Argument List

AVRH, AVRT	$(\tilde{U}_{S2}/\tilde{U}_{S1})_H$, $(\tilde{U}_{S2}/\tilde{U}_{S1})_T$	, Axial velocity ratio
CØRH, CØRT	C_H, C_T	, Chord (dimensionless)
DELSIH, DELSIT	Δ^*_{1H}, Δ^*_{2H}	, Displacement thickness (dimensionless)
RHØIH, RHØIT	$\tilde{P}_{1H}$, $\tilde{P}_{1T}$	, Density (dimensionless)
TEMH, TEMT	$\tilde{\ }_{1H}$, $\tilde{\ }_{1T}$	, Temperature (dimensionless)
UIH, UIT	$\tilde{U}_{1H}$, $\tilde{U}_{1T}$	, Total upstream velocity (dimensionless)
U2H, U2T	$\tilde{U}_{2H}$, $\tilde{U}_{2T}$	, Total downstream velocity (dimensionless)
Y	Y	, Distance from wall (dimensionless)
YT	Y_T	, Duct height (dimensionless)
ZEWLØS	Z_{EW}	, End wall loss coefficient

Internal Variables

AN1, AN2	N_1, N_2	, Power law
CF	C_f	, Friction coefficient
DEL1H, DEL1T	Δ_{1H}, Δ_{1T}	, Boundary layer thickness (dimensionless)
DEL2H, DEL2T	Δ_{2H}, Δ_{2T}	, Boundary layer thickness (dimensionless)
H1, H2	H_1, H_2	, Shape factor (dimensionless)
RETH	Re_θ	, Reynolds number based on momentum thickness

Internal Variables

THET1H, THET1T	θ_{1H}, θ_{1T}	, Momentum thickness (dimensionless)
THET2H, THET2T	θ_{2H}, θ_{2T}	, Momentum thickness (dimensionless)

Theory

The interaction of the blade boundary layer (profile loss) with the endwall boundary layer is treated by adding an endwall loss to the blade force calculation procedure. This endwall loss is based on empirical correlations developed by Papaliou (Ref. 1) and is described in detail in Ref. 2.

References

1. Papailiou, K. D., R. Flot, and J. Mathieu: Secondary Flows in Compressor Bladings, ASME J. of ENg. For Power, Vol. 99, April 1977, pp. 211-224.

2. Anderson, O. L., G. B. Hankins, D. E. Edwards: Extension to an Analysis of Turbulent Swirling Compressible Flow for Application to Axisymmetric Small Gas Turbine Ducts. UTRC Report R81-915395-12, NASA CR 165597, February 1982.

Subroutine FAVER2

Object

Solve for mass flow weighted average flow

Options

None

List of Symbols

AAR	$= \mathcal{R}$	, Area ratio (dimensionless)
AMA	$= M$	, Local Mach number (dimensionless)
AMACHE	$= \widetilde{M}$	, Area average Mach number (dimensionless)
AMFH	$= (G\mathring{M}/V)_H$	, Wall bleed hub (dimensionless)
AMFT	$= (G\mathring{M}/V)_T$	, Wall bleed tip (dimensionless)
AMG	$= M_{MID}$	, Midpoint Mach number (dimensionless)
AMM	$= M_{MAX}$	, Maximum Mach number (dimensionless)
ASH	$= A_{SH}$	, Surface area hub wall (dimensionless)
AST	$= A_{ST}$	, Surface area tip wall (dimensionless)
ATFH	$= (GQ/V)_H$	, Heat flux/length hub (dimensionless
ATFT	$= (GQ/V)_T$	, Heat flux/length tip (dimensionless
BWORK		, Work input (dimensionless)
CPC	$= P_r/q_1$	, Normalizing factor for Cp (dimensionless)
CPCØMP	$= C_{PC}$	, Pressure coefficient compressible (dimensionless)
CPINC	$= C_{PI}$	, Pressure coefficient incompressible (dimensionless)
DASH1,DASH2	$= \Delta A_{SH}$	, Area increment hub (dimensionless)
DAST1,DAST2	$= \Delta A_{ST}$	, Area increment tip (dimensionless)

DENTP1, DENTP2	$= \Delta\bar{I}$	, Change in Entropy (dimensionless)
DISP	$= \bar{\Phi}$	, Dissipation function (dimensionless)
DPSTI1, DPSTI2	$= \Delta\bar{\psi}$	, Increment in mass flow (dimensionless)
DQSH1, DQSH2	$= \Delta\tilde{Q}_H$	, Increment in heat flow hub (dimensionless)
DQST1, DQST2	$= \Delta\tilde{Q}_T$	, Increment in heat flow tip (dimensionless)
DTHEO1, DTHEO2	$= \Delta\bar{\Theta}_o$	, Increment in total temperature (dimensionless)
ENTP	=	, Entropy (dimensionless
PIO	$= \pi_o$	, Average total pressure (dimensionless)
PIOO	$= \pi_{oo}$	, Average inlet total pressure (dimensionless)
PSI	$= \bar{\psi}$	, Mass flow (dimensionless)
PSIO	$= \bar{\psi}_o$	, Initial mass flow (dimensionless)
QM	$= 1/2(PU^2)_{MAX}$	, Freestream dynamic pressure (dimensionless)
QSH	$= \tilde{Q}_H$	, Total heat flow hub (dimensionless)
QST	$= \tilde{Q}_T$	, Total heat flow tip (dimensionless)
RØM	$= P_{max}$	, Freestream density (dimensionless)
RUM	$= (PU)_{MAX}$	, Maximum momentum (dimensionless)
THEO	$= \bar{\Theta}_o$	, Average total temperature (dimensionless)
THEOO	$= \bar{\Theta}_{oo}$	, Inlet average total temperature (dimensionless)
UM	$= U_{MAX}$	, Freestream velocity (dimensionless)

<u>Theory</u>

The mass flow weighted average quantity ϕ is defined by

$$\bar{\phi} = \frac{1}{\Psi} \int_0^1 \frac{GPU_S}{V} \phi \, dn \tag{1}$$

where

$$\bar{\Psi} = \int_0^1 \frac{GPU_S}{V} dn \tag{2}$$

The area is given by

$$A = \int_0^1 \frac{G}{V} dn \tag{3}$$

It is noted that the mass flow weighted averages satisfy certain conditions

$$\frac{d\bar{\Psi}}{dS} = \left(\frac{G\mathring{M}}{V}\right)_T f \left(\frac{G\mathring{M}}{V}\right)_H \tag{4}$$

$$\frac{d}{dS}(\bar{\Psi}\bar{\Theta}_o) = \left[\frac{G\mathring{M}\Theta_o}{V}\right]_T + \left[\frac{G\mathring{M}\Theta_o}{V}\right]_H - \frac{\gamma}{\gamma-1}\left[\left(\frac{GQ}{V}\right)_T - \left(\frac{GQ}{V}\right)_H\right] \tag{5}$$

The entropy is related to the dissipation by

$$\frac{d}{dS}(\Psi\bar{I}) = \left(\frac{G\mathring{M}I}{V}\right)_T + \left(\frac{G\mathring{M}I}{V}\right)_H - \frac{\gamma}{\gamma-1}\left[\left(\frac{GQ}{V\Theta}\right)_T - \left(\frac{GQ}{V\Theta}\right)_H\right]$$
$$- \frac{\gamma}{\gamma-1}\int_0^1 \frac{GQ}{V\Theta^2}\frac{d\Theta}{dn} dn$$
$$+ \gamma M_r \int_0^1 \frac{G}{\Theta V^2}\left[\Sigma_{ns}E_{ns} + \Sigma_{n\phi}E_{n\phi} + \Phi_R\right] dn \tag{6}$$

Eq. (4) states that the mass flow is the net flow crossing the wall boundary. Eq. (5) states that the total energy flux is the net crossing the boundary walls. Thus, for an adiabatic wall, the mass flow weighted average total temperature is constant. Finally, Eq. (6) states that the entropy flux is the net crossing the boundary plus the change due to the dissipation function and heat fluxes. Then using the definition of entropy we have

$$\frac{\bar{\Pi}_{02}}{\bar{\Pi}_{01}} = \left(\frac{\bar{\Theta}_{02}}{\bar{\Theta}_{01}}\right)^{\frac{\gamma}{\gamma-1}} \exp\left[\bar{I}_2 - \bar{I}_1\right] \tag{7}$$

and the loss coefficient is given by

$$C_{PL} = \frac{\bar{P}_{01} - \bar{P}_{02}}{\bar{P}_{01} - \bar{P}_1} = \frac{1 - \bar{P}_{02}/\bar{P}_{01}}{1 - \bar{P}_1/\bar{P}_{01}} = \frac{1 - \bar{\Pi}_{02}/\bar{\Pi}_{01}}{1 - \bar{\Pi}_1/\bar{\Pi}_{01}} \tag{8}$$

If we now defined the mass flow weighted averages

$$\bar{\Pi}_0 = a_r \int_0^1 \frac{G}{V} \frac{\Pi^2}{\sqrt{\Theta}} M \left(1 + \frac{\gamma-1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}} dn \tag{9}$$

$$\bar{\Theta}_0 = a_r \int_0^1 \frac{G}{V} \pi \sqrt{\Theta} M \left(1 + \frac{\gamma-1}{2} M^2\right) dn \tag{10}$$

$$\bar{\Psi} = a_r \int_0^1 \frac{G}{V} \frac{\pi}{\sqrt{\Theta}} M \, dn \tag{11}$$

and assume that the dependent variables have a small error E defined by

$$\left.\begin{aligned}
\bar{\Pi}' &= (1+\varepsilon_{\Pi})\Pi \\
\bar{\Theta}' &= (1+\varepsilon_{\Theta})\Theta \\
\bar{M}' &= (1+\varepsilon_{M})M \\
\bar{\Pi}_0' &= (1+\varepsilon_{\Pi_0})\Pi_0 \\
\bar{\Theta}_0' &= (1+\varepsilon_{\Theta_0})\Theta_0 \\
\bar{\Psi}' &= (1+\varepsilon_{\Psi})\bar{\Psi}
\end{aligned}\right. \tag{12}$$

We may determine the values of E to correct the solution to satisfy the mass flow weighted average equations. Thus, if we substitute Eq. (12) into Eq. (9) through Eq. (11) and keep first order terms in E,

$$\left.\begin{aligned}
\varepsilon_{\Theta} &= \varepsilon_{\Theta_0} - \varepsilon_{\Psi} \\
\varepsilon_{\Pi} &= \varepsilon_{\Pi 0} - \varepsilon_{\Psi} \\
\varepsilon_{\Pi} &= \frac{\varepsilon_{\Theta_0}}{2} + \frac{3}{2}\varepsilon_{\Psi} - \varepsilon_{\Pi 0} \\
\varepsilon_{\rho} &= \varepsilon_{\Pi} - \varepsilon_{\Theta} \\
\varepsilon_{u} &= \frac{\varepsilon_{\Theta}}{2} - \varepsilon \\
\varepsilon u_{\phi} &= \varepsilon u \sin\bar{\alpha} \\
\varepsilon u_{s} &= \varepsilon u \cos\bar{\alpha}
\end{aligned}\right\} \tag{13}$$

where

$$\left.\begin{aligned}
\varepsilon_{\Pi 0} &= \bar{\Pi}_0'/\bar{\Pi} - 1 \\
\varepsilon_{\Theta_0} &= \bar{\Theta}_0'/\bar{\Theta}_0 - 1 \\
\varepsilon_{\Psi} &= \bar{\Psi}'/\bar{\Psi} - 1
\end{aligned}\right\} \tag{14}$$

Thus the prime quantities are calculated From Eq. (9) through Eq. (11) and the unprimed quantities from Eq. (4) through Eq. (6).

The pressure coefficient is defined by

$$\bar{C}_P = \frac{\bar{\Pi} - \bar{\Pi}_1}{\bar{\Pi}_{01} - \bar{\Pi}_1} \tag{15}$$

An effective area $\tilde{A}$ can be defined as the geometrical area minus the blockage caused by the boundary layer. If we define the freestream as the point of maximum velocity across the duct we have by definition

$$\rho_\infty U_\infty A_{eff} = \mathring{m} = (\Psi_T - \Psi_H) N_B \tag{16}$$

Hence, the blockage B is defined as

$$B = 1 - A/A_{eff} = 1 - m/(\rho_\infty U_\infty A) \tag{17}$$

The area averaged (effective Mach number) may then be defined by the isentropic flow relations. Thus,

$$\frac{A_{eff}}{A} = \frac{M_{eff}}{M} \left[\frac{1 + \frac{\gamma-1}{2} M_\infty^2}{1 + \frac{\gamma-1}{2} M_{eff}^2} \right]^{\frac{1}{2} \frac{\gamma+1}{\gamma-1}} \tag{18}$$

The effectiveness η of the diffuser is based on an ideal isentropic flow with the mass flow weighted average Mach numbers. Thus, the ideal pressure coefficient is given by

$$C_{PI} = \frac{\tilde{\Pi} - \bar{\Pi}_1}{\bar{\Pi}_{01} - \bar{\Pi}_1} \tag{19}$$

where

$$\frac{\Pi_{01}}{\tilde{\Pi}} = \left[1 + \frac{\gamma-1}{2} \tilde{M}^2 \right]^{\frac{\gamma}{\gamma-1}} \tag{20}$$

$$\frac{A}{A_1} = \frac{\overline{M}_1}{\widetilde{M}} \left[\frac{1 + \frac{\gamma - 1}{2} \widetilde{M}^2}{1 + \frac{\gamma - 1}{2} \overline{M}_1^2} \right]^{\frac{1}{2} \frac{\gamma + 1}{\gamma - 1}} \tag{21}$$

Then

$$\eta = \overline{C}_P / C_{PI} \tag{22}$$

The wall friction coefficient is defined as

$$C_f = \Sigma w \Big/ \left(\frac{1}{2} \rho U^2\right)_{MAX} \tag{23}$$

The wall surface area and heat flow are determined by integrating the equations

$$A_S = \int_0^S \frac{2 \pi R}{V} \, dS \tag{24}$$

$$\widetilde{Q}_S = \int_0^S \frac{2 \pi R Q}{V} \, dS \tag{25}$$

using the trapezoid rule.

Function FCØLES (ARG. LIST)

Object

Compute Coles' velocity profile

Options

None

ARG. LIST

AK	$= \kappa$	, Von Karmen constant
AKPL	$= K^{+}$	, Rougness Reynolds No.
API	$= \Pi_c$	, Coles' shape factor
APLS	$= A^{+}$	, Van Driest constant
BPL	$= B^{+}$	, Law of wall constant
DELT	$= \delta$	, Boundary layer thickness (dimensionless)
Y	$= y$	, Distance from wall (dimensionless)
YPLS	$= y^{+}$	, Universal distance

List of Symbols

FCØLES	U^{+}	, Universal velocity

Theory

This subroutine constructs Coles' velocity profile (see Ref. 1). For $y^{+} > 20$ Coles' profile is valid and is given by

$$U^{+} = \frac{1}{\kappa}\left\{\left[\ln Y^{+} + B^{+}\right] + 2\Pi_c \sin^2\left(\frac{\pi}{2} y/\delta\right)\right\} \tag{1}$$

where the constant of integration for the law of the wall is obtained from the rough wall model function BPLUSR.

For $y^{+} < 20$, the velocity in the sublayer is obtained by integrating the equation (see Ref. 2)

$$\frac{dU^+}{dY^+} = \frac{2}{1 + \left[1 + (2\kappa Y^+ D)^2\right]^{1/2}} \qquad (2)$$

The damping factor D for a smooth wall is given by Van Driest (Ref. 2)

$$D = 1 - \exp(-Y^+/A^+) \qquad (3)$$

and for a rough wall it is given by McDonald (Ref. 3)

$$D = 1 - \exp(-Y^+/A^+) + \left[1 + \frac{K^+}{90\,Y^+}\right] \exp\left(2.3\,\frac{Y^+}{K^+}\right) \qquad (4)$$

References

1. Coles, D.: Law of the Wake in the Turbulent Boundary Layer. J. Fluid Mechanics, Vol. 1, 1956.

2. Van Driest, E. F.: On Turbulent Flow Near a Wall. J. Aeronautical Sciences, Vol. 23, No. 11, 1956.

3. McDonald, H., and R. W. Fish: Practical Calculations of Transitional Boundary Layers. Int. J. of Heat and Mass Transfer, Vol. 16, No. 9, 1973.

Subroutine FCØRCT

Object

Correct solution based on mass flow average

Options

None

List of Symbols

AMUW	$= \mu_w/\mu_r$	, Wall value of viscosity (dimensionless)
DU	$= \Delta U$	, Velocity difference (dimensionless)
ECØR	$= (\rho U)/(\rho U)_m$	, Mass flux ratio (dimensionless)
EMB	$= E_m$	, Error in Mach number (dimensionless)
EPB	$= E_p$	, Error in static pressure (dimensionless)
ERB	$= E$	, Error in density (dimensionless)
ETB	$= E_T$	, Error in static temperature (dimensionless)
EUB	$= E_U$	, Error in velocity (dimensionless)
EUP	$= E_{U\phi}$	, Error in swirl velocity (dimensionless)
EUS	$= E_{US}$	, Error in streamwise velocity (dimensionless)
EW	$= E$	, Strain

Theory

Corrections are applied to the flow variables according to the theory outlined in Subroutine FAVER2. In addition, the point-to-point instability described in Ref. (1) is minimized by recalculating the stresses and heat flux using central differences rather than centered differences. The corrections from FAVER2 are currently set to zero.

Reference

1. Keller, H. B.: A New Difference Scheme for Parabolic Problems. Numerical Solutions of Partial Differential Equations. II SYNSPADE 1970, Academic Press, N.Y.

Subroutine FCPLX

Object

Evaluates Schwartz Christoffel transformation

Options

LØPT=1 Compute and store functions and derivatives
=2 Compute only derivatives

List of Symbols (Note subscript notation for derivatives used)

N1,N2	$= N_1, N_2$
XS	$= S$
XN	$= n$
XSX	$= S_x = n_y$
XSY	$= S_y = n_x$
XD	$= D$
XZETS	$= \xi_S = \eta_n$
XETAS	$= \eta_s = -\xi_n$
XXS	$= x_s = y_n$
XYS	$= y_s = x_n$
XB1	$= \tilde{X} = \xi_x = \eta_y$
YB1	$= \tilde{Y} = -\xi_y = \eta_x$
X1	$= x$
Y1	$\doteq y$
XDB	$= \bar{D}$
XNZET	$= n_\xi$
XNETA	$= n_\eta$
XV	$= V$

XSXX	$= S_{xx} = n_{xx} = s_{yy}$
XSXY	$= S_{xy} = n_{yy} = n_{xx}$
XXSS	$= X_{ss} = y_{ns} = x_{nn}$
XXSN	$= X_{sn} = y_{nn} = -y_{ss}$
XB2	$= \tilde{\tilde{X}} = \xi_{xx} = \eta_{yx} = -\xi_{xy}$
YB2	$= \tilde{\tilde{Y}} = -\xi_{xy} = -\eta_{yy} = \eta_{xx}$
XZSS	$= \xi_{ss} = \eta_{sn} = -\xi_{nn}$
XZSN	$= \xi_{sn} = \eta_{nn} = -\eta_{ss}$
XDBN	$= \bar{D}_n$
XDBS	$= \bar{D}_s$
XESDN	$= (\eta_s/\bar{D})_n$
XESDN	$= (\eta_s/\bar{D})_s$
XZSDN	$= (\xi_s/\bar{D})_n$
XZSDS	$= (\xi_s/\bar{D})_s$
XYN	$= V_n$
XVS	$= V_s$
XESS	$= \eta_{ss}$
XESN	$= \eta_{sn}$
XDIS	$= D_s$
XDIN	$= D_n$

<u>Theory</u>

The theory for evaluating the complex functions and all derivatives is derived in Ref. (1). With the use of orthogonality relations which are implicit in the theory of complex function, the functions and derivatives may be evaluated. It is noted that this subroutine was programmed to accept multiple sources in the z plane, although they are not used in the present calculation. The derived functions calculated in this subroutine are listed as follows:

$$S = \sum_{I=1}^{NS} \frac{A_I}{2} \ln\left[(X-b_I)^2 + y^2\right] \tag{1}$$

$$n = \sum_{I=1}^{NS} A_I \tan^{-1}\left[y/(X-b_I)\right] \tag{2}$$

$$S_x = \sum_{I=1}^{NS} \frac{A_I\,(X-b_I)}{\left[(X-b_I)^2+y^2\right]} \tag{3}$$

$$S_y = \sum_{I=1}^{NS} \frac{A_I\,y}{\left[(X-b_I)^2+y^2\right]} \tag{4}$$

$$S_{xx} = \sum_{I=1}^{NS} \frac{A_I}{\left[(X-b_I)^2+y^2\right]} \left\{1 - \frac{2(X-b_I)^2}{\left[(X-b_I)^2+y^2\right]}\right\} \tag{5}$$

$$S_{yy} = -\sum_{I=1}^{NS} \frac{A_I\,2y(X-b_I)}{\left[(X-b_I)^2+y^2\right]} \tag{6}$$

$$D = -(S_x^2 + S_y^2) \tag{7}$$

$$X_s = -\, S_x/D \tag{8}$$

$$Y_s = -\, S_y/D \tag{9}$$

$$\xi_s = \xi_x X_s + \xi_y Y_s \tag{10}$$

$$\eta_s = \eta_x X_s + \eta_y Y_s \tag{11}$$

$$V = \frac{1}{\left[\xi_s^2 + \xi_n^2\right]^{1/2}} \tag{12}$$

$$D_s = -\left[2 S_y (S_{yx} X_s + S_{yy} Y_s) + 2 S_x (S_{xx} X_s + S_{xy} Y_s)\right] \tag{13}$$

$$D_n = -\left[2 S_y (S_{yx} X_n + S_{yy} Y_n) + 2 S_x (S_{xx} X_n + S_{xy} Y_n)\right] \tag{14}$$

$$X_{ss} = -\left[\frac{S_{xx} X_s + S_{xy} Y_s}{D} - \frac{S_x D_s}{D^2}\right] \tag{15}$$

$$X_{sn} = -\left[\frac{(S_{xx}X_n + S_{xy}Y_n)}{D} - \frac{S_x D_n}{D^2} \right] \tag{16}$$

$$\xi_{ss} = \xi_x X_{ss} + \xi_{xx} X_s^2 + 2\xi_{xy} Y_s X_s + \xi_y Y_{ss} + \xi_{yy} Y_s^2 \tag{17}$$

$$\xi_{sn} = \xi_x X_{sn} + \xi_y Y_{sn} + (\xi_{yy} - \xi_{xx}) Y_s X_s + \xi_{xy} (X_s^2 - Y_s^2) \tag{18}$$

$$V_s = -V^3 / \left[\xi_s \xi_{ss} + \xi_n \xi_{ns} \right] \tag{19}$$

$$V_n = -V^3 / \left[\xi_s \xi_{sn} + \xi_n \xi_{nn} \right] \tag{20}$$

Numerical accuracy can be significantly improved by ordering the way in which sums and products are made. As an example, the first equation, Eq. (7.2.29.1), may be written,

$$S = \sum_{I=1}^{NS} A_I \left\{ |X - b_I| \left[1 + \left(\frac{y}{X - b_I} \right)^2 \right]^{1/2} \right\} \qquad |X - b_I| > |y|$$

$$= \sum_{I=1}^{NS} A_I \left\{ |y| \left[1 + \left(\frac{X - b_I}{y} \right)^2 \right]^{1/2} \right\} \qquad |y| > |X - b_I|$$

Thus the square root of the sum of squares of O(1) and $S = O(/X - b_I/)$. This rule has been applied to all equations by extracting the order of magnitude of the term from each calculation and products and quotients allowed to cancel order of magnitude terms.

Subroutine FETA (B, ETA, AN, DEDN, D2EDN)

Object

Calculate distorted mesh to be used in Subroutine PØIS

Options

$B = 0$	Uniform mesh (no stretching)
$B > 0$	Tanh stretching

Variables

B		, Constant
ETA	η	, Transformed Normal Coordinate
AN	n	, Normal Coordinate
DEDN	$\partial\eta/\partial n$	
D2EDN	$\partial^2\eta/\partial n^2$	

Theory

This subroutine calculates the distorted mesh that will be used in calculation by subroutine PØIS. The transformation is given by

$$\left.\begin{aligned} \eta &= \tanh[Bn]/\tanh[B] && B > 0 \\ \eta &= n && B = 0 \end{aligned}\right\} \qquad (1)$$

Subroutine FINTG(IKL)

Object

Integrate equations of Schwartz-Christoffel transformation

Options

IKL = Number of streamlines

List of Symbols

IKL , Number of streamlines

Theory

Four simultaneous ordinary differential equations are integrated using a third order Runge-Kutta numerical integration method. These equations from the Schwartz-Christoffel transformation (Ref. 1) are denoted symbolically as,

$$\left.\begin{aligned} \frac{dX}{dS} &= X_S(X,Y) \\ \frac{dY}{dS} &= Y_S(X,Y) \\ \frac{d\xi}{dS} &= \xi_S(X,Y) \\ \frac{d\eta}{dS} &= \eta_S(X,Y) \end{aligned}\right\} \qquad (1)$$

The Runge-Kutta formulas applied to the first equation are

$$\left.\begin{aligned} B_{11} &= \Delta S X_S(X,Y) \\ B_{12} &= \Delta S X_S(X+B_{11}/2\ ,Y+B_{21}/2) \\ B_{13} &= \Delta S X_S(X+2B_{12}-B_{11}\ ,Y+2B_{22}-B_{21}) \end{aligned}\right\} \qquad (2)$$

$$X(S+\Delta S) = X(S) + (B_{11} + 4B_{12} + B_{13})/6 \qquad (3)$$

Reference

1. Anderson, O. L.: User's Manual for a Finite Difference Calculation of Turbulent Swirling Compressible Flow in Axisymmetric Ducts with Slot Cooled Walls. Vols. I. and II, USAAMRDL-TR-74-50, 1974.

Subroutine FINVIS (LØPT)

Object

Calculate upstream/downstream blade force variables

Options

LØPT	= 1	Calculate upstream flow variables
	= 2	Calculate downstream pressure
	= 3	Calculate downstream flow variables
IØPT10	= 0	Stator
	= 1	Rotor
IDBG7	= 0	No debug printout
	= 1	Debug printout

List of Symbols

A(I,K)	=	$a_{I,K}$	, Coefficients of differential equations
EPS	=	ε	, Maximum error in ψ
ERR	=	$\lvert\hat{\psi}^{\nu+1}-\hat{\psi}^{\nu}\rvert$	, Error in stream function
ERRBKP	=	$\lvert\hat{U}^{\nu+1}_{s2}-\hat{U}^{\nu}_{s2}\rvert/\hat{\nu}_{s2}$	, Error in streamwise velocity
ITER	=	ν	, Iteration counter
PSIHT	=	$\hat{\Psi}$	, Upstream mass flow (dimensionless)
PSIMAX	=	$\hat{\Psi}_{MAX}$	, Maximum mass flow (dimensionless)
PSIT	=	$\hat{\Psi}^{\nu}$	, νth guess for Ψ (dimensionless)
PSI1	=	$\hat{\Psi}^{\nu}_{1}$	, νth guess for upper bound (dimensionless)
PSI2	=	$\hat{\Psi}^{\nu}_{2}$	, νth guess for lower bound (dimensionless)
XL	=	X_L	, Lower bound on x
XM	=	X_{MIN}	, X for choked flow
XU	=	X_U	, Upper bound on x
XX	=	$X\ (\hat{P}/\hat{P}_o)^{\frac{\gamma-1}{\gamma}}$	, Pressure ratio
X1	=	X^{ν}_{1}	, νth guess for upper bound
X2	=	X^{ν}_{2}	, νth guess for lower bound

Theory

The blade force is calculated using the blade element theory described in Ref. (1). Subroutine FINVIS calculates the flow variables just upstream of the blades (Station JLE) and just downstream of the blades (Station JTE). This data is used by subroutine FØRCE to calculate the force applied to the flow by the blades.

LØPT = 1 Calculate Upstream Flow

The inviscid flow field without blades is calculated by subroutine CALINV and stored on unit NCALV. The location of the upstream and downstream stations (JLE, JTE) are calculated by subroutine SLETE. Data from the JLE(th) station is read from unit NCALV by subroutine FØRCE. All the flow field variables may then be calculated using the isentropic flow relations and the equation of state. Velocities in both the relative (rotor) and absolute (stator) are calculated. Finally a first guess for the downstream density and streamwise velocity is calculated for use by the backpressure iteration in subroutine FØRCE.

LØPT = 2 Calculate Downstream Pressure

Subroutine CASC which is called by subroutine FØRCE calculates the total pressure loss and downstream flow angle. For stators these are calculated in the absolute frame of reference and for rotors these are calculated in the relative frame of reference. The work is calculated using the rotor speed and the upstream and downstream tangential velocities in the Euler equation. For stators the work input is zero. For rotors the work input is not known until the downstream tangential velocity is determined. This requires the backpressure iteration loop in subroutine FØRCE. With total pressure, total temperature, and flow angle known, the downstream flow field is solved using the radial momentum equation and the global continuity equation with the algorithm described in subroutine CKINPT.

LØPT = 3 Calculate Downstream Flow Variables

When the downstream static pressure is determined the flow variables are calculated using the isentropic relations and the equation of state.

Reference

1. Barber, T. J., P. Raghuraman, and O. L. Anderson: Evaluation of an Analysis for Axisymmetric Internal Flows in Turbomachinery Ducts. ASME Winter Meeting - Flow in Primary Nonrotating Passages in Turbomachines, p. 107, December 1979.

Subroutine FLINE

Object

Find coordinates of output data line

Options

IWALL	= 1	OD Wall
	= 2	ID Wall
MØLD	= 1	Side (JX, KX), (JX+1, JX)
	2	Side (JX+1, KX), (JX+1, KX+1)
	3	Side (JX+1, KX+1), (JX, KX+1)
	4	Side (JX, KX+1), (JX, KX)

Variables

JBH, JBT	, Wall intersection index (see Fig. 1)
JX, KX	, Corner point index (see Fig. 1)
LX	, Input data point index (see Fig. 1)
MØLD	, Old intersection index
MNEW	, New intersection index
(RB1, ZB1) = $(\bar{R}_1, \bar{Z}_1)$	, Cartesian coordinates of point LX-1 (dimensionless)
(RB2, ZB2) = $(\bar{R}_2, \bar{Z}_2$	, Cartesian coordinates of point LX (dimensionless)
(RXH, ZXH) = (R_H, Z_H)	, ID wall intersection (dimensionless)
(RXT, ZXT) = (R_T, Z_T)	, OD wall intersection (dimensionless)
(SB1, ANB1) = $(\bar{s}_1, \bar{n}_1)$	, Streamline coordinates of point LX-1
(SB], ANB2) = $(\bar{s}_2, \bar{n}_2)$	, Streamline coordinates of point LX
SX, TX = S, T	, Interpolation parameters for coordinate line and input data line
XBL = $\bar{X}_1$	, Distance from inlet LX=1
XBL = $\bar{X}_{LLAST}$	, Diatance from inlet LX=LLAST
XB2 = $\bar{X}_{LX}$	, Distance from inlet LX=LX
XXH, XXT = X_H, X_T	, See Fig. 1

Theory

A pair of points on the coordinate grid is selected according to the index MNEW and a straight line in parametric form is constructed with S as a parameter. Then a pair of points (LX, LX-1) is selected and a straight line is constructed in parametric form with T as a parameter. If the two lines intersect within the two pairs of points, then the input data line intersects the grid line. This calculation is done with subroutine CRØSS1.

The search procedure is initiated by finding the intersection of the input data line with the walls using subroutine ALINE. Then starting at the ID wall, the three sides of the coordinate rectangle are searched using subroutine CRØSS2 with the point (JX, KX) as the corner point (side MØLD is skipped) and the intersection with side MNEW determined. Then the neighboring coordinate rectangle is searched (see Fig. 8). This procedure continues until a coordinate rectangle is found that contains the input data point LX.

When a coordinate rectangle contains the point LX, the streamline coordinates ($\bar{s}_2$, $\bar{n}_2$) are calculated by interpolation using subroutine CLINE. Subroutine DLINE stores the appropriate data.

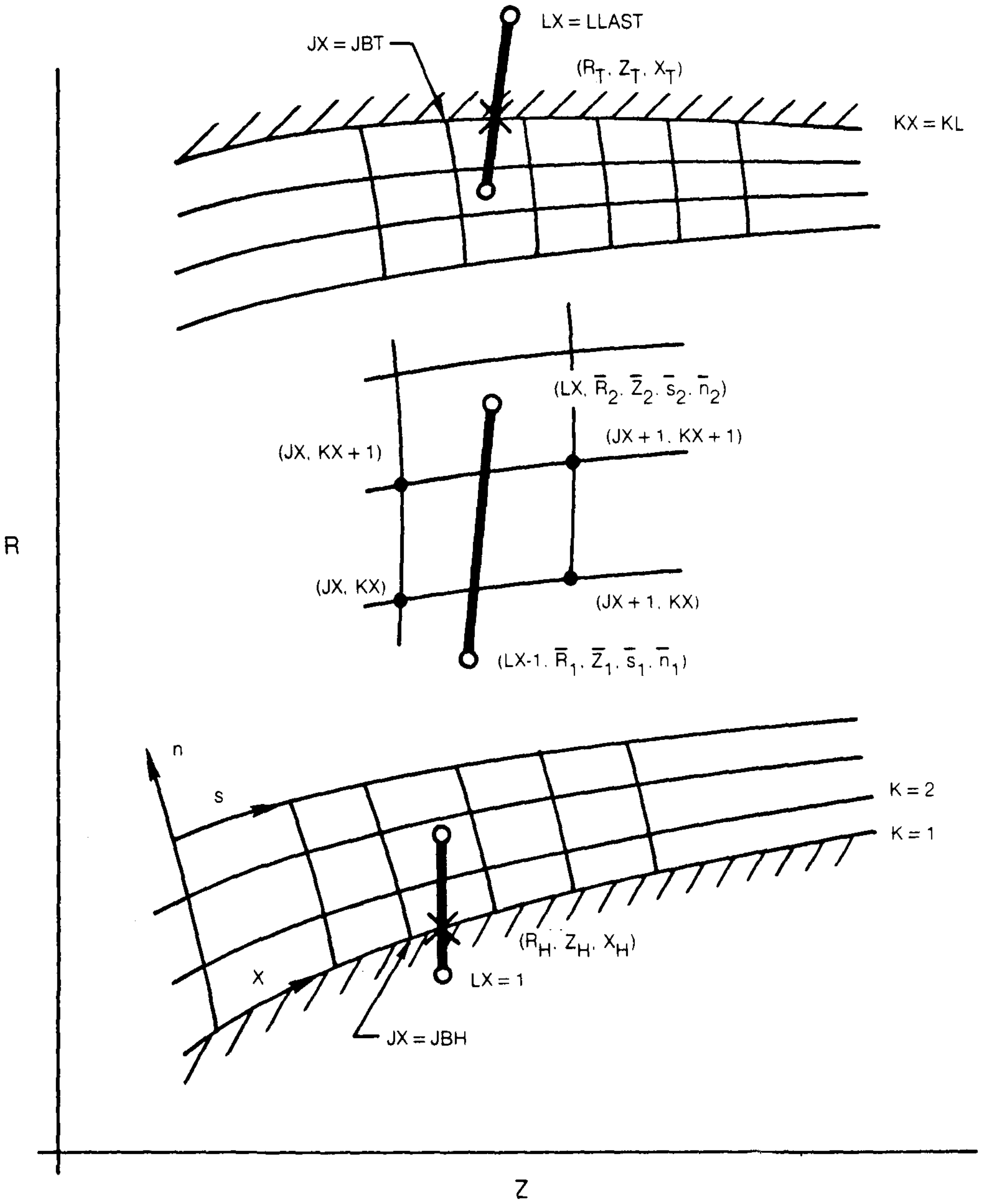


Fig. 8. Intersection of Input Data Line with Coordinate Grid

Subroutine FLØWIN

Object

Set up initial flow conditions

Options

IDBG3 = 0	No debug
= 1	Print debug
IØPT1 = 3, 4, 7, 8, 9	Inlet flow option (see Section 4.2)
IØPT11 = 0	Duct flow
= 1	External flow
IØTP12 = 0, 1, 2, 3	Turbulence model option (see Section 4.2)
NØPT4 = 1	ID wall boundary condition
= 2	ID axis of symmetry boundary condition
NØPT5 = 0	Continue calculating
> 0	Fatal error - stop calculation
NØPT18 = 0	Flag - turbulent flow
= 1	- laminar flow
NØPT19 = 1	Print DIAGNØSTIC's
> 1	Do not print DIAGNØSTIC's
DRØUGI = 0	Smooth wall
> 0	Rough wall
RHS(10),RTS(10) = 0	Adiabatic wall boundary condition
> 0	Wall temperature boundary condition

List of Symbols

AKAPAC	= κ ,	Prandtl constant
AMACHE	= $\tilde{M}$,	Area average Mach number
AMACH1	= $\bar{M}$,	Mass average Mach number
AMIH, AMIT	= M_e ,	Edge Mach number (hub, tip)
AMUIH, AMUIT	= μ_e/μ_r ,	Edge viscosity (hub, tip)

AMUWH, AMUWT	$= \mu_w/\mu_r$	,	Wall viscosity (hub, tip)
ANH, AWT	$= n$	,	Power law
APLUSC	$= A^+$	,	Van Driest constant
AKPLUS	$= K^+$	,	Rough wall Reynolds number
APRES1	$= \bar{P}$	,	Mass average static pressure (psf)
APRS01	$= \bar{P}_o$	,	Mass average total pressure (psf)
ATEMP	$= \bar{T}_c$	,	Mass average static temperature (°R)
A2CF	$= C_f/2$	,	Wall friction coefficient
BBO	$= B_o$	,	Blockage
BPLS	$= B^+$	,	Constant in law of wall
CFRS	$= C_{fR}/C_{fS}$	,	Ratio rough/smooth wall friction
DIH, DIT	$= \delta/r_r$	,	Boundary layer thickness (hub, tip)
DSH, DST	$= \delta^+/r_r$	,	Displacement thickness (hub, tip)
DRØUGH	$= d/r_r$	,	Equivalent sand roughness height
H12H, H12T	$= H_{12}$	,	Shape factor (hub, tip)
IBL		,	Flag - inner loop iteration
ITDEL		,	Inner loop iteration counter
ITER		,	Outer loop iteration counter
KH, KT		,	Index boundary layer edge (hub, tip)
PIH, PIT	$= \Pi_c$	,	Cole's shape parameter (hub, tip)
RIH, RIT	$= \rho_e/\rho_r$	,	Edge density (hub, tip)
RØWH, RØWT	$= \rho_w/\rho_r$	,	Wall density (hub, tip)
RETH, RETT	$= Re_\theta$	,	Reynolds numbers - momentum thickness
SIGWH, SIGWT	$= \Sigma_w$	,	Wall stress (dimensionless)
TIH, TIT	$= \theta_e$	,	Edge temperature (hub, tip) (dimensionless)
TWH, TWT	$= \theta_w$	,	Wall temperature (hub, tip) (dimensionless)
UIH, UIT	$= u_e$	,	Edge velocity (hub, tip) (ft/sec)
USH, UST	$= u^*$	,	Friction velocity (hub, tip) (ft/sec)
YABS	$= Y$	,	Distance from wall (dimensionless)

YPLUS	$= Y^+$	,	Universal distance
GAMMA	$= \gamma$	,	Ratio of specific heats

Theory

The general analysis is shown by the flow chart in Fig. 9 and takes place in the following steps:

1. Calculate total pressure P_T, total temperature T_T, swirl angle α, and an initial guess for the static pressure P from the input data according to the inlet flow option IØPT1.

2. Calculate Mach number M, static temperature P, density ρ, and velocity components from the input data and the isentropic flow relations given by

$$\frac{P_0}{P} = \left(1 + \frac{\gamma-1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}} \tag{1}$$

$$T_0 = 1 + \frac{\gamma-1}{2} M^2 \tag{2}$$

$$c = (\gamma \mathcal{R} T)^{1/2} \tag{3}$$

$$u = Mc \tag{4}$$

$$u_s = u \cos \alpha \tag{5}$$

$$u_\phi = u \sin \alpha \tag{6}$$

3. Find edge of boundary layer. On the first iteration the edge of the turbulent boundary layer is estimated by the displacement thickness and power law (Ref. 1),

$$\delta = (1 + n)\,\delta^* \tag{7}$$

and for laminar flow using the Blasius profile (Ref. 1)

(8)

On successive iterations the edge of the boundary layer is estimated from Cole's profile (Ref. 2) as shown in Step 4. When δ is known, flow variables at the edge of the boundary layer may be determined by interpolation of the core flow variables.

4. Calculate boundary layer profiles. With the edge conditions known, the boundary layer velocity profile is constructed from the Blasius solution using a linear interpolation in function UBLAS. For turbulent flow the velocity profile is constructed from Cole's profile, for which the following relations hold:

$$\frac{u}{u^*} = \frac{1}{\kappa}\left\{\ln\left(\frac{\rho_w u^* Y}{\mu_w}\right) + B^+ + 2\Pi_c \sin^2\left(\frac{\pi}{2}\frac{y}{\delta}\right)\right\} \tag{9}$$

$$\frac{u_e}{u^*} = \frac{1}{\kappa}\left\{\ln\left(\frac{\rho_w u^* \delta}{\mu_w}\right) + B^+ + 2\Pi_c\right\} \tag{10}$$

$$\kappa\frac{u_e}{u^*}\frac{\delta^*}{\delta} = 1 + \Pi_c \tag{11}$$

$$\left(\kappa\frac{u_e}{u^*}\right)^2\frac{\theta}{\delta^*} = \kappa\frac{u_e}{u^*}(1 + \Pi_c) - (2. + 3.2\,\Pi_c + 1.55\,\Pi_c^2) \tag{12}$$

$$H_{12} = \delta^*/\theta \tag{13}$$

Equation (11) may be substituted into (10) to obtain

$$\frac{u_e}{u^*} = \frac{1}{\kappa}\left\{\ln\left(\frac{\rho_w u^*\delta}{\mu_w}\right) + B^+ + 2\left(\kappa\frac{u_e}{u^*}\frac{\delta^*}{\delta} - 1\right)\right\} \tag{14}$$

With u_e, ρ_w, μ_w and a guess for δ, Eq. (14) may be solved for U^* using function CFCØLE. Equation (11) may be substituted in Eq. (12) to obtain

$$\left(\kappa \frac{u_e}{u^*}\right)^2 \frac{\theta}{\delta^*} = \kappa \frac{u_e}{u^*} (1 + \Pi_c) - \left[2 + 3.2\phi + 1.55\phi^2\right] \tag{15}$$

where

$$\phi = \kappa \frac{u_e}{u^*} \frac{\delta^*}{\delta} - 1 \tag{16}$$

and Eq. (15) may be solved for Cole's shape factor, Π_e. Then the parameters for constructing Cole's velocity profile (Eq. 9) are known. A new guess for the edge of the boundary layer is obtained from Eq. (11).

6. Check inner loop for convergence

$$|\delta^{\nu+1} - \delta^{\nu}| / \delta^{\nu} < \phi \tag{17}$$

7. Calculate new static pressure. The normal momentum equation (Ref. 3) is integrated in subroutine ERPIN.

8. Check outer loop for convergence

$$|P^{\nu+1} - P^{\nu}| / P^{\nu} < \phi \tag{18}$$

When the static pressure converges, the subroutine also returns the weight flow WFLØ for use in the weight flow iteration by subroutine WFITER.

<u>References</u>

1. Schlicting, H.: Boundary Layer Theory. 6th Ed., McGraw-Hill, New York, 1968.

2. Coles, D. E.: The Law of the Wake in the Turbulent Boundary Layer. J. Fluid Mech, Vol. 1, 1956, p. 191.

3. Anderson, O. L.: Calculation of Internal Viscous Flows in Axisymmetric Ducts at Moderate to High Reynolds Numbers. Int. J. Computers and Fluids, Vol. 8, No. 4, p. 391, December 1980.

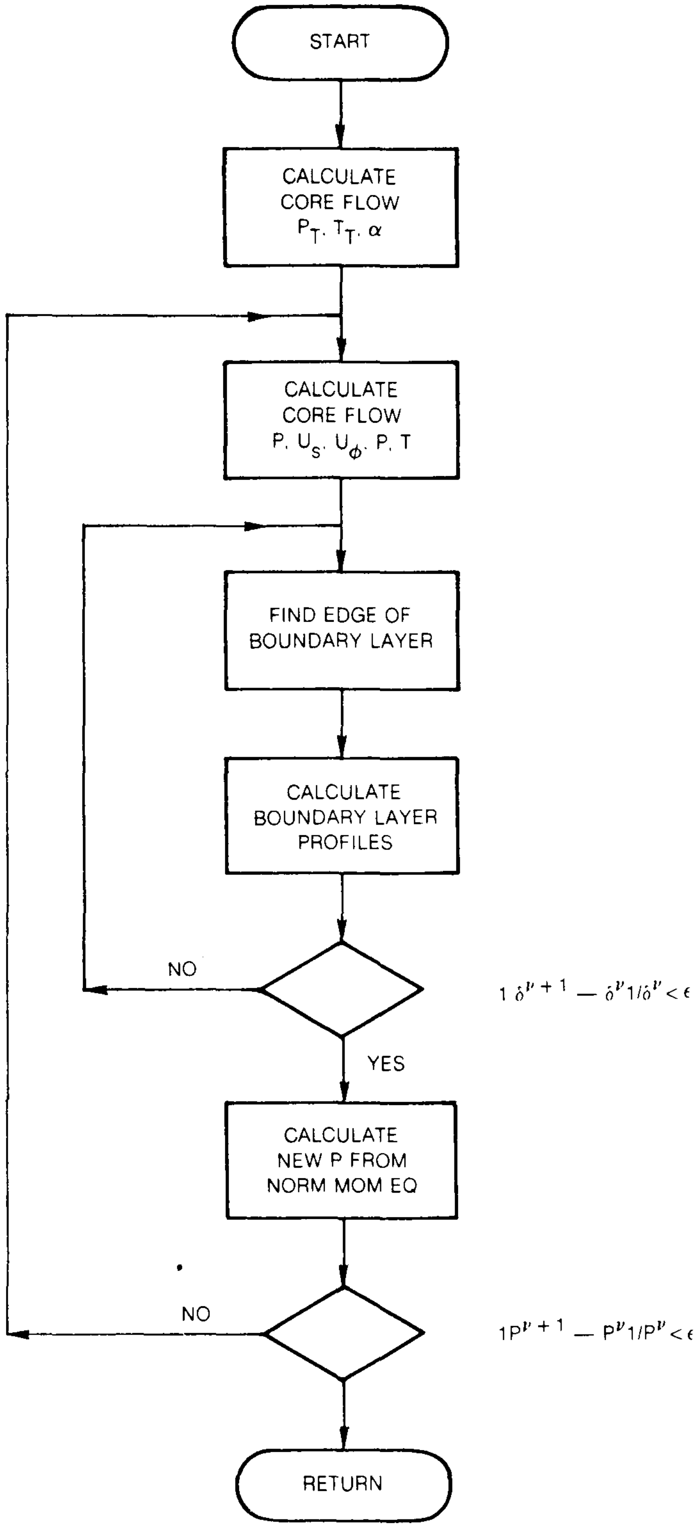


Fig. 9. Flow Chart for Subroutine Flowin

Subroutine FNØRM

Object

Normalize input variables

Options

None

List of Symbols

AM	$= \mu$	, Viscosity (slug/ft/sec)
AMACH	$= M$	, Mach number
APO	$= P_o$	, Total pressure (psfa)
ATO	$= T_o$	, Total temperature (deg R)
DELT	$= \theta$	, Momentum thickness (ft)
DTHE	$= \theta/h$	, Momentum thickness/duct height
ETA	$= \eta_\delta$	, η coordinate at δ
H12	$= H_{12}$	, Shape factor
PHI	$= \phi_\delta$	
RETH	$= Re_\theta$	, Reynolds number
RØU	$= \rho_\infty u_\infty$	, Freestream mass flow/area (slug/ft^2/sec)
TEST	$= \eta_T$	, Test on η coordinate
XI	$= \varepsilon$	, Roberts transformation parameter
YPLUS1	$= Y_1^+$	, Universal distance to first mesh point
ZETA	$= \zeta_\delta$	, ζ coordinate at δ
	δ	, Boundary layer thickness (ft)
	δ^*	, Displacement thickness (ft)
	h	, Duct height (ft)

Theory

This subroutine performs the following tasks:

1. Normalize all input variables list of variables in Section 8.0
2. Set gas properties to default values if not specified
3. Selects the mesh distortion parameter DDS if not specified.

The mesh distortion parameter is selected in the following manner. From Ref. (1), the Roberts transformation can be written,

$$\phi = \exp\left\{2 \ln\left(\frac{c+1/2}{c+1/2}\right)(\eta - 1/2)\right\} \tag{1}$$

$$n = \frac{(c+1/2)\,\phi - (c-1/2)}{1+\phi} \tag{2}$$

With c given and η specified at uniformly distributed mesh points, n may be determined. The parameter c can be related to the mesh distortion at the boundary. Thus,

$$\frac{1}{DDS} = \left.\frac{dn}{d\eta}\right|_{\eta=0} = \frac{\phi(0)}{1+\phi(0)}\; 2\,(c+1/2) \ln\left(\frac{c+1/2}{c-1/2}\right) \tag{3}$$

For turbulent boundary layers, the first mesh point from the wall is set at $Y^+ = 1$. Hence,

$$Y_1^+ = \frac{u\, y_1}{\nu} \simeq \frac{\Delta\eta}{DDS}\, Re_\theta \sqrt{\frac{C_f}{2}}\, \frac{h}{\theta} \tag{4}$$

where

$$\theta = \delta \,/\, H_{12} \tag{5}$$

$$Re_\theta = \rho_\infty\, u_\infty\, \theta / \mu \tag{6}$$

For laminar flow, 1/3 of the mesh points are placed in the boundary layer. Hence,

$$\begin{aligned} n_\delta &= 3\,\delta^*/h \\ \eta_\delta &= 0.3 \end{aligned} \tag{7}$$

Equation (7) may be substituted into Eqs. (11) and (2) to solve for c and into Eq. (3) to solve for DDS. Let

$$c = 1/2 + \epsilon \tag{8}$$

where ε is generally a small number. Then

$$\phi \simeq n_\delta/(1-n_\delta) \tag{9}$$

$$b = 1/(2\eta_\delta - 1) \tag{10}$$

$$\epsilon = 1/(\phi^b - 1) \tag{11}$$

$$DDS = \left[\frac{2\epsilon}{1+\epsilon/(1+\epsilon)} \ln\left(\frac{1+\epsilon}{\epsilon}\right)\right]^{-1} \tag{12}$$

These equations have a minimum distortion DDS. Let

$$n_T = (2\cdot 2^{1/b} - 1)/(1 + 2^{1/b}) \tag{13}$$

If $n_\delta > n_T$, $\varepsilon = 1$.

Subroutine FØRCE (LØPT)

Object

Calculate blade force/span

Options

LOPT	= 1	Calculate blade force
	= 2	Print variables
IØPT2	= 1	Calculate blade force from input data
	2	Not in use
	3	Calculate blade force from cascade data
	4	Calculate force from input loss and air angle
IØPT6	= 0	Blade force is calculated
	= 1	Thickness effects only
IØPT10	= 0	Stator
	= 1	Rotor
NØPT5	= 0	Continue calculation
	> 0	Error - Stop calculation

List of Symbols

ALIND	$= \alpha_i$	, Induced angle of attack (deg.)
ALPHS	$= \alpha_s$	, Stagger angle (deg.)
AMACHI	$= M_i$	, Absolute Mach number (stator) , Relative Mach number (rotor)
ANGI, ANG2	$= \alpha_1, \alpha_2$	, Absolute flow angles (stator) (deg.)
	β_1, β_2	, Relative flow angles (rotor) (deg.)
CHØRD	$= C/r_r$	, Chord
CX21	$= U_{s2}/U_{s1}$	, Streamwise velocity ratio
ERRBKN	$\lvert\hat{U}^{\mu+1}_{s2}-\hat{U}^{\mu}_{s2}\rvert/\hat{U}_{s2}$	, Error
ITER	$= \mu$	, Back pressure iteration counter
JCL		, Centerline station
JLE		, Leading edge station
JTE		, Trailing edge station

ØMEGZ	$= r_r \Omega / u_r$	, Rotor speed
PHIC	$= \phi_c$	, Camber angle (deg)
RHØCX	$= (\hat{P}\hat{U}_{s2})/(\hat{P}\hat{U}_{s1})$	, Mass flow ratio
SOLD	$= \sigma$	, Solidity
THIKM	$= t/c$	, Thickness/chord
THIKN	$= t/r_r$	, Thickness
WIND	$= W_i$	, Induced velocity (dimensionless)

Theory

The analysis for calculating the blade force is described in Ref. 1. Three input options are in use.

IØPT2 = 1 Calculate Force From Input Data

If the flow variables upstream and downstream of the blade row are known, the blade force can be calculated directly.

IØPT2 = 2 Calculate Force From Cascade Data

The flow just upstream of the blade is calculated by subroutine CALINV and stored on unit NCALV. This data is read from unit NCALV using subroutine BLKRED and used by subroutine FINVIS(1) to set up all the upstream flow variables. Subroutine CASC calculates the downstream flow angle and loss coefficient. Subroutine FINVIS(2) calculates the downstream static pressure, and FINVIS(3) calculates all the remaining flow variables. For stators (IØPT10 = 0) a back pressure iteration is not required if the RHØCX corrections are not used in subroutine CASC.

IØPT2 = 4 Calculate Force Input Loss and Flow Angle

The loss coefficient and exit flow angle may be obtained from input data cards replacing the output from subroutine CASC. The remaining algorithm is the same as IØPT2 = 3.

IØPT = 2 Print Solution

This code is self explanatory.

Reference

1. Barber, T. J., P. Raghuraman, and O. L. Anderson: Evaluation of an Analysis for Axisymmetric Internal Flows in Turbomachinery Ducts. ASME Winter Meeting - Flow in Primary Nonrotating Passages in Turbomachinery. p. 107, December 1979.

Subroutine FØRCL

Object

Compute blade force/volume

Options

IØPT6 = 0 Use blade force

= 1 Use thickness effects only

List of Symbols

GAP	= G	, Gap (dimensionless)
ZLE	= Z_{LE}	, Location of leading edge (dimensionless)
ZTE	= Z_{TE}	, Location of trailing edge (dimensionless)

Theory

The force per unit span is calculated by subroutine FØRCE. This subroutine calculates the force per unit volume by dividing by gap and projected chord length according to Ref. 1.

Reference

1. Anderson, O. L.: User's Manual for a Finite Difference Calculation of Turbulent Swirling Compressible Flow in Axisymmetric Ducts with Struts and Slot Cooled Walls. USAAMRDL-TR-74-50, Vol. 1, 1974.

Subroutine GBLADE

Object

Interpolate blade parameters

Options

IØPT2	= 0	No blade force
	> 0	Blade force see Page I-13
LØPT2	= 0	Calculate blade blockage
	= 1	Do not calculate blade blockage

List of Symbols

See CØMMØN /ACØNSØ/

Theory

This subroutine linearly interpolates the blade parameters

Subroutine FØUTP

Object

Interpolation solution on output data line

Options

NLAST = 0 , Return

> 0 , Interpolate Solution

List of Symbols

EPS	E	,	Small increment in Y
FI1(I)	$f_I(n,s_{J+1})$	,	n interpolated solution at J+1 (dimensionless)
FI2(I)	$f_I(n,s_{J+2})$	,	n interpolated solution at J+2 (dimensionless)
FI(I,L)	$f_I(n,s)$	,	Interpolation solution at n,s (dimensionless)
GAP	G	,	Blade gap (dimensionless)
Jx1,Jx2,Kx1,kx2		,	Four corners of interpolation grid
NLAST	N	,	Number of points on data line
THTS(K)	Θ	,	Angle between streamline and Z axis (rad.)
RHP,ZHP	R_H, Z_H	,	ID coordinate of output data line (dimensionless)
RTP,ZTP	R_T, Z_T	,	OD coordinate of output data line (dimensionless)
RWH,ZWH	R_{WH}, Z_{WH}	,	Intersection with ID wall
RWT,ZWT	R_{WT}, Z_{WT}	,	Intersection with OD wall

Theory

The coordinates of the end points of the output data line (RHP,ZHP,RTP,ZTP) are read and normalized. These points must lie outside the duct to resolve ambiguities in the interpolation procedure. The intersection of the output data line with the ID wall (RWH, ZWH) and the OD wall (RWT, ZWT) is determined using subroutine ALINE. The output data line between the ID and OD wall intersections is divided into NLAST-3 intervals for NLAST data points which include the end points. Since the second and next to last point must be inside the duct, the points (RWH, ZWH, RWT, ZWT) are moved by an amount E. The location of the NLAST points in the (n,s) coordinates is determined using subroutine FLINE. The output data point is then located within the rectangular grid bounded by (J+1, K+1; J+2, K+1; J+1, K+2; J+2, K+2) and the solution can be calculated using linear interpolation.

Function FTHIK (Z,IS,LØP)

Object

Calculate blade thickness

Option

LØP	= 1	FTHIK = t/c
	= 2	FTHIK = d(t/c)/d(X/c)
IS	= 1	NACA 5 digit series airfoil
	= 2	Parabolic airfoil
	= 3	NACA 5 digit series airfoil
	= 4	Input thickness distribution
	= 5	NACA 65A series airfoil

Theory

The NACA series airfoil shapes are given in Ref. 1 and selected by the blade shape parameter IS.

Reference

1. Abbot, I. H. and A. E. Von Doenhoff: Theory of Wing Sections, Dover Pub., 1959.

Subroutine GDUCT

Object

Calculate duct shape

Options

IØPT3	= 1	Straight annular duct
	= 2	Arbitrary duct with evenly spaced axial stations
	= 3	Straight wall annular diffuser
	= 4	Duct shape stored on file JDRUM
	= 5	Arbitrary duct with arbitrary stations
NØPT4	= 1	No ID wall
	= 2	ID wall

List of Symbols

AREAR	$= r_r^2$	, Reference area (ft^2)
DUCTI(N)		, Duct input parameters
JL		, Number of streamwise stations
JLPTS		, Number of input points
KNØTS		, Number of nodes for spline fit
R(1,1,J),R(1,4,J)	$= R_T, Z_T$	, Output coordinates OD wall (dimensionless)
R(2,1,J),R(2,4,J)	$= R_H, Z_H$	, Output coordinates ID wall (dimensionless)
RD1I(J), ZD1I(J)	$= r_{TI}, z_{TI}$	, Input coordinates of OD wall (ft)
RD2I(J), ZD2I(J)	$= r_{HI}, z_{HI}$	, Input coordinates of ID wall (ft)
RADR	$= r_r$	, Reference radius (ft)
Z1	$= z_1$	, Duct axial length (ft)

Theory

For IØPT3 = 1 or 3, the duct shape is calculated for JL equally spaced axial stations using algebraic relations with DUCTI(N) as parameters. For IØPT3 = 4, the geometry and coordinates are read from data file JDRUM. For IØPT3 = 2 or 5, the least squares spline fitting and smoothing routine SMØØTH is used. For IØPT3 = 2, the independent variable is the axial distance with evenly spaced axial stations. For IØPT3 = 5, the independent variable is the distance along the wall which may be arbitrarily spaced.

Subroutine INIT

Object

Set all CØMMØN block variables to zero

Options

None

Theory

This subroutine sets all CØMMØN block variables to zero which are defined in Section 6.2 in the Manual. Subroutine IZERØ sets all integer variable and subroutine ZERØ sets all real variables.

Subroutine INITF

Object

Initialize data file parameters for inviscid solution

Option

None

Variables

FIV (1, L, K) ψ , Stream function (dimensionless)

FIV (2, L, K) U_s, Streamwise Velocity (dimensionless)

FIV (3, L, K) U_ϕ, Tangential Velocity (dimensionless)

FIV (4, L, K) Π , Static Pressure (dimensionless)

FIV (5, L, K) I , Entropy (dimensionless)

FIV (6, L, K) Θ , Static Temperature (dimensionless)

FIV (7, L, K) ρ , Density (dimensionless)

FIV (8, L, K)

FIV (9, L, K)

FIV (10, L, K)

L = 1 @ J-1 station

L = 2 @ J station

L = 3 @ J+1 station

K = 1, KL streamlines

FIPARM (1) ρ_r, Reference density, (slug/ft^3)

FIPARM (2) T_r, Reference temperature, (°Rankin)

FIPARM (3) P_r, Reference pressure, (psf abs)

Variables (Cont'd)

FIPARM (4) = g , Gravitational constant (ft/sec)

FIPARM (5) = μ_r , Reference viscosity (slug/ft/sec)

FIPARM (6) = C_p , Specific heat constant pressure ($ft^2/sec^2/°R$)

FIPARM (7) = C_v , Specific heat constant volume ($ft^2/sec^2/°R$)

FIPARM (8) = R , Gas constant ($ft^2/sec^2/°R$)

FIPARM (9) = P_{r_T} , Prandtl number turbulent

FIPARM (10) = Not used

FIPARM (11) = u_r , Reference velcoity (ft/sec)

FIPARM (12) = NOPT7, Number of blocks stored inviscid solution

FIPARM (13) = , Not used

FIPARM (14) = IØPT15 , First station

FIPARM (15) = IØPT16 , Last station

Theory

This subroutine initializes the dependent variable array FIV which is stored on a disk file and sets all parameters FIPARM required by the calculation.

Subroutine INITFV

Object

Initialize data file parameters for viscous solution

Option

None

Variables

FIV (1, L, K) ψ , Stream function (dimensionless)

FIV (2, L, K) U_s, Streamwise Velocity (dimensionless)

FIV (3, L, K) U_ϕ, Tangential Velocity (dimensionless)

FIV (4, L, K) Π , Static Pressure (dimensionless)

FIV (5, L, K) I , Entropy (dimensionless)

FIV (6, L, K) Θ , Static Temperature (dimensionless)

FIV (7, L, K) ρ , Density (dimensionless)

FIV (8, L, K)

FIV (9, L, K)

FIV (10, L, K)

L = 1 @ J-1 station

L = 2 @ J station

L = 3 @ J+1 station

K = 1, KL streamlines

FIPARM (1) ρ_r, Reference density, (slug/ft^3)

FIPARM (2) T_r, Reference temperature, (°Rankin)

FIPARM (3) P_r, Reference pressure, (psf abs)

Variables (Cont'd)

FIPARM (4) = g , Gravitational constant (ft/sec)

FIPARM (5) = μ_r , Reference viscosity (slug/ft/sec)

FIPARM (6) = C_p , Specific heat constant pressure ($ft^2/sec^2/°R$)

FIPARM (7) = C_v , Specific heat constant volume ($ft^2/sec^2/°R$)

FIPARM (8) = R , Gas constant ($ft^2/sec^2/°R$)

FIPARM (9) = P_{r_T} , Prandtl number turbulent

FIPARM (10) = Not used

FIPARM (11) = u_r , Reference velcoity (ft/sec)

FIPARM (12) = NOPT7, Number of blocks stored inviscid solution

FIPARM (13) = NOPT8 , Number of blocks stored, viscous station

FIPARM (14) = IØPT15 , First station

FIPARM (15) = IØPT16 , Last station

Theory

This subroutine initializes the dependent variable array FIV which is stored on a disk file and sets all parameters FIPARM required by the calculation.

Subroutine INITQ

Object

Initialize data file parameters for Q array

Option

None

Variables

BLOCK(1)	JSTEP	, Block (record number)
Q(1,K)	R	, Radius (dimensionless)
Q(2,K)	Z	, Axial distance (dimensionless)
Q(3,K)	$\partial R/\partial n$	, Derivative
Q(4,K)	$\partial R/\partial s$	, Derivative
Q(5,K)	$(\cos\theta)^2_{axi}$	, Axisymmetric flow angle
Q(6,K)	V	, Metric coefficient (dimensionless)
* Q(7,K)	$\partial V/\partial n = (K_s + \Delta K_s)$	, Curvature of streamline
Q(8,K)	$\partial V/\partial s$	, Curvature of potential line
Q(9,K)	X	, Distance along streamline (dimensionless)
Q(10,K)	Y	, Duct height (dimensionless)
Q(11,K)	Y/Y_T	, Normalized duct height
Q(12,K)	A	, Duct Area (dimensionless)
Q(13,K)	G	, Gap (dimensionless)
Q(14,K)	$\partial G/\partial n$	, Derivative
Q(15,K)	$\partial G/\partial s$	, Derivative
Q(16,K)	$\partial \eta/\partial n$	, Transformation of normal coordinate

Variables (Cont'd)

Q(17,K)		, Not used
Q(18,K)	n	, Normal coordinate (dimensionless)
Q(19,K)	η	, Transformed coordinate
	K = 1, KL	
QPARM(1)	r_r	, Reference radius, (ft)
QPARM(2)		, Not used
QPARM(3)	JL	, Number of streamwise steps
QPARM(4)	KL	, Number of streamlines

Theory

This subroutine initializes the independent variable array BLOCK which is stored on a disc file and sets all parameters QPARM required by the calculation.

* Note that Q(7,K) stores either K_s or $K_s+\Delta K_s$.

Subroutine INTFRE

Object

Initialize freestream conditions

Options

None

List of Symbols

See CØMMØN BLØCKS

Theory

Data read from file NDRUM is used to set up the freestream conditions for subroutine PØIS.

Subroutine IZERØ (IADDR, NUM)

Object

Set integer variables to zero

Options

None

List of Symbols

IADDR	Integer array name
NUM	Number of elements in array

Theory

This subroutine sets the first NUM elements of integer array IADDR to zero.

Subroutine MINVRT(A,B,N)

Object

Invert NxN Matrix

Options

None

List of Symbols

A	$= \bar{\bar{A}}$	, Augmented $\bar{\bar{A}}$ matrix
B	$= \bar{\bar{B}}$	, Augmented $\bar{\bar{B}}$ matrix ($\bar{\bar{A}}^{-1}$) matrix
N		, Number of equations (rows)
M		, Number of columns

Theory

The $\bar{\bar{A}}$ matrix is inverted using the Gauss-Jordin elimination procedure. First the augmented $\underset{\sim}{\bar{\bar{A}}}$ N, M is formed including the identity matrix,

$$\underset{\sim}{\bar{\bar{A}}} = (A \; I) \tag{1}$$

Then the following revision formula is used

$$b_{I-1,J-1} = a_{I,J} - a_{1J}a_{I1}/a_{11} \qquad \begin{Bmatrix} 1 < I \leq N \\ 1 < J \leq M \end{Bmatrix} \tag{2}$$

$$b_{N,J-1} = a_{1J}/a_{11} \qquad 1 < JM \tag{3}$$

Note that the $\bar{\bar{B}}$ matrix has one less column than the $\underset{\sim}{\bar{\bar{A}}}$ matrix. Then the substitution is made

$$a_{IJ} = b_{IJ} \qquad \begin{array}{l} 1 \le T \le N \\ 1 \le J \le M-1 \end{array} \qquad (4)$$

and then repeated until the $\bar{\bar{B}}$ matrix is an NxN matrix or the $\bar{\bar{A}}^{-1}$ matrix.

Subroutine ØRTFUN

Object

Set up coordinate functions used in SØLVI

Options

None

List of Variables

Q(J,K)	=	Coordinate functions at station J
G(1,K)	= $[G/V]^{J}_{K-1/2}$	
G(2,K)	= $[XY]^{J}_{K-1/2}$	
G(3,K)	= $[G(XV)]^{J}_{K-1/2}$	
G(4,K)	= $[\frac{1}{XV}\frac{\partial V}{\partial n}]^{J}_{K-1/2}$	
G(5,K)	= $[\frac{1}{XR}\frac{\partial R}{\partial n}]^{J}_{K-1/2}$	
G(6,K)	= $[\frac{1}{XR}\frac{\partial R}{\partial s}]^{J}_{K-1/2}$	
G(7,K)	= $[\frac{V}{XG}\frac{\partial}{\partial n}(\frac{G}{V})]^{J}_{K-1/2}$	
G(8,K)	= $[\frac{V}{XG}\frac{\partial}{\partial n}(\frac{G}{V})-\frac{1}{XY}\frac{\partial V}{\partial n}]$	
G(9,K)	= $[\frac{V}{XG}\frac{\partial}{\partial n}(\frac{G}{V})-\frac{1}{XR}\frac{\partial R}{\partial n}]^{J}_{K-1/2}$	
G(9+I,K)	= G(I,K) @ J-1, I=1,9 K=1, KL	
DF(1,K)	= $[H_s/XV]^{J}_{K-1/2}$	Streamwise blade force/volume (dimensionless)
DF(2,K)	= $[H_\phi/XV]^{J}_{K-1/2}$	Tangential blade force/volume (dimensionless)
DF(3,K)	= $[\Phi_B/XV]^{J}_{K-1/2}$	Total pressure loss/volume (dimensionless)
DF(4,K)	= $[X]^{J}_{K-1/2}$	Coordinate distortion (dimensionless)
DF(5,K)	= $[H_s/XV]^{J-1}_{K-1/2}$	Streamwise blade force/volume (dimensionless)

DF(6,K) = $[H_\phi/XV]_{K-1/2}^{J-1}$ Tangential blade force/volume (dimensionless)

DF(7,K) = $[\Phi_B/XV]_{K-1/2}^{J-1}$ Total pressure loss/volume (dimenionless)

DF(8,K) = $[X]_{K-1/2}^{J-1}$ Coordinate distortion (dimenionless)

where

$X = d\eta/dn$

Theory

The variables G and DF are calculated in this subroutine in order to be used in subroutine SØLVI.

Subroutine ØUTPUT

Object

Print title page

Option

None

List of Symbols

None

Theory

This subroutine prints the title page which records all modifications, dates, and references to changes incorporated into the ADD code.

Subroutine PØIS (RESM,ITER)

Object

Solve Poisson equation

Option

IDBGP	= 0	No debug printout
	= 1	Printout residuals
	= 2	Print solution

List of Symbols

P(K,J)	=	ψ	, Stream function (dimensionless)
F(K,J)	=		, Coefficient (1/PG) (dimensionless)
PSI(K)	=	$\tilde{\psi}$	, Iterative guess for J
ITER	=	ν	, Iteration counter
RLX			, Relaxation factor
RESMAX	=	ε_{MAX}	, Maximum residual accepted
RESDM	=	ε_{M}	, Maximum residual/J station
RESM	=	ε	, Maximum residual/sweep

Theory

The solution algorithm is described in Reference 1.

References

1. Anderson, O. L. and D. E. Edwards: Extension to an Analysis of Turbulent Swirling Compressible Flow in Axisymmetric Ducts, NASA Contract NAS3-21853, 1981, UTRC Report R81-914720.

Subroutine PØISCF

Object

(1) Set of coefficients of $\nabla^2 \psi = 0$
(2) Set boundary conditions on ψ
(2) Set initial guess for ψ

Options

IDBG17	= 0	Compressible Flow
	= 1	Incompressible Flow
IDBGT	= 0	No debug test case
	= 1	Debug test case
IDBGP	= 0	No debug test printout
	= 1	Debug printout

Variables

Q(I,K)			, Coordinate functions
FIV(I,L,K)			, Dependent variables for inviscid flow
P(K)	=	ψ_K^J	, Stream function at station J
A(K)	=	$GP/V/(d\eta/dn)$	, Coefficient for $\partial\psi/\partial\eta$
F(K)	=	$1/G/P$	, Coefficient of $\nabla^2 \psi$
G(K)	=	$V/G/P$	, Coefficient for velocity calculation
R(K)	=	P	, Density ratio (ρ/ρ_r)
T(K)	=	Θ	, Temperature ratio (T/T_r)
V(K)	=	V	, Metric coefficient dimensionless
GAP	=	G	, Gap (g/r_r)
VMET	=	V	, Metric coefficient (dimensionless)
RHØ	=	P	, Density ratio (ρ/ρ_r)
TEM	=	Θ	, Temperature ratio (T/T_r)
USO	=	U_{so}	, Upstream constant velocity (u_o/u_r)

USINF	$U_{s\infty}$	,Free stream axial velocity $(u_{s\infty}/u_r)$
UPINF	$U_{\phi\infty}$	,Free stream tangential velocity $u_{\phi\infty}/u_r$
PSIKL	ψ_∞	,Free stream stream function (dimensionless)
TEMINF	θ_∞	,Free stream static temperature ratio (T/T_r)
RHOINF	P_∞	,Free stream density ratio (ρ/ρ_r)
AMINF	M_∞	,Free stream Mach number
PTINF	Π_∞	,Free stream total pressure ratio (P_0/P_r)
BLK		,See COMMON/SPCGD/

Theory

This subroutine does the following steps

(1) Reads coordinate Q file and solution FIV file
(2) Interpolates the solution to the (η,S) grid
(3) Calculates the coefficient $F = 1/PG$
(4) Calculates coefficients BLK for streamline curvature calculation
(5) Sets boundary condition on Ψ
(6) Calculates initial guess for Ψ
(7) Stores F, BLK, P on disk files

The initial guess is given by the inviscid solution obtained from CALINV. The boundary conditions are given by:

$$\psi(0,s) = 0 \tag{1}$$

$$\psi(1,s) = \psi_\infty \tag{2}$$

$$\psi(\eta,0) = U_{so}\int_0^{\eta}\left(\frac{GP}{V}\Big/\frac{d\eta}{dn}\right)_{s=0} d\eta \tag{3}$$

$$\psi(\eta,s_L) = U_{so}\int_0^{\eta}\left(\frac{GP}{V}\Big/\frac{d\eta}{dn}\right)_{s=s_L} d\eta \tag{4}$$

Subroutine PØISØN

Object

Calculate axisymmetric streamline curvature

Options

IØPT7	=	0	No curvature corrections
	=	1	Curvature correction
IDBG15	=	0	Use input KL streamlines
	>	0	Use IDBG15 streamlines

List of Symbols

IRHØ	,Density iteration counter
ITERL	,Maximum number of iterations
KHØLD	,No. ADD code streamlines
KL	,No. SCURVA streamlines
RESMAX	,Maximum residual for convergence

Theory

This subroutine is a calling subroutine for subroutines INTFRE, PØISCF, PØIS, and SCURVA

Subroutine PRTØUT

Object

Calculate and print certain terms neglected in ADD code equations

Options

IØPT18 = 0 Do not print terms
= 1 Print terms

IØPT4 Print every IØPT4 station

List of Symbols

JFIRST		, First calculated station
JLAST		, Last calculated station
KL		, Number of streamlines
DS	Δs	, Stepsize in streamwise
DETA	$\Delta\eta$	, Stepsize in transformed normal direction
REY	Re_r	, Reference Reynolds number
F		, Flow array
Q		, Geometry array
VARBL (1, J, K)	ψ	, Stream Function (dimensionless)
VARBL (2, J, K)	U_s	, Streamwise Velocity (dimensionless)
VARBL (3, J, K)	U_ϕ	, Swirl Velocity (dimensionless)
VARBL (4, J, K)	ρ	, Density (dimensionless)
VARBL (5, J, K)	Σ_{ns}	, Streamwise stress (dimensionless)
VARBL (6, J, K)	$\frac{\mu_E}{\mu_r}$	, Effective Viscosity (dimensionless)
VARBL (7, J, K)	R	, Radius (dimensionless)
VARBL (8, J, K)	Z	, Axial Distance (dimensionless)
VARBL (9, J, K)	V	, Metric Scale Coefficient (dimensionless)

VARBL (10, J, K)	=	G	,Gap (dimensionless)
VARBL (11, J, K)	=	$\frac{\partial R}{\partial s}$	,Streamwise Derivative of radius
VARBL (12, J, K)	=	$\frac{\partial V}{\partial n}$	,Curvature of potential line
VARBL (13, J, K)	=	$-\frac{\partial V}{\partial s}$	,Curvature of stream line
VARBL (14, J, K)	=	y/h	,Fractional distance across duct

Output Variables

Q(11, K)	(Y/Y_T)	Fractional distance across duct
UDUDS	$P\, U_s \frac{\partial U_s}{\partial s}$	
UN2V	$P\, U_n^2/V \frac{\partial V}{\partial s}$	
UUNV	$P\, U_s\, U_n/V \frac{\partial V}{\partial n}$	
UDUNDS	$P\, U_s \frac{\partial U_n}{\partial s}$	
DUN2DN	$P\, U_n \frac{\partial U_n}{\partial n}$	
UDUPDS	$P\, U_s \frac{\partial U_\phi}{\partial s}$	
UNUPR	$P\, U_n\, U_\phi/R \frac{\partial R}{\partial s}$	
DSIGNS	$V/G \frac{\partial}{\partial n} (G/V\, \Sigma_{ns})$	
DSIGNP	$V/G \frac{\partial}{\partial s} (G/V\, \Sigma_{s\phi})$	
UN	$-V/G\, P \frac{\partial \psi}{\partial s}$	
DSIGSS	$V/G \frac{\partial}{\partial s} (G/V\, \Sigma_{ss})$	

Theory

In the formation of the ADD code equations from the Navier-Stokes equations certain terms were assumed negligible. This subroutine calculates some of the neglected terms.

Subroutine QINTER

Object

Interpolate curvature from PØIS mesh to SØLVI mesh

Options

None

List of Symbols

Q(J,K)	Coordinate functions

Theory

After the curvature and flow angle has been calculated from the potential flow solution, this subroutine interpolates to obtain values at the numerical grid points which will be used in the SØLVI calculation.

Subroutine QPTMAX (QMAX,PTMAX,RUMAX)

Object

Calculate maximum total and dynamic pressure

Options

None

List of Symbols

PTMAX	P_{OM}	Maximum total pressure (psfa)
QMAX	q_M	Maximum dynamic pressure (psfa)
RUMAX	ρu_M	Maximum mass flow rate (slug/ft^2/sec)

Theory

At any given streamwise station, this subroutine searches through the solution for the maximum velocity. The total and dynamic pressure are calculated at the point across the duct where the velocity is a maximum.

Subroutine RDCØR(J) Coordinate Block

Object

Read J and J+1

Options

None

List of Symbols

J ,Block number

Theory

Coordinate data is read into core using BLKRED.

Subroutine READPF(J,JJ)

Object

Read P and F files in NIST word blocks

Option

None

List of Symbols

J	J	,Record number
JJ	JJ	,Record number in block N
N	N	,Block number
F	F	,Coefficients of $\nabla^2\psi = 0$
P	ψ	,Stream function (dimensionless)
NST	= 25	,Number of records per block
NBK		,Number of words to move pointer
NIST		,Number of words per block
NFDRM	= 23	,Coefficient file number F array
NL		,Last block number
NBIST		,Number of words for two records
NMOVE		,Number of words to move pointer

Theory

The entire F and P arrays cannot be kept in core at the same time so that the I/O is arranged to keep fixed blocks in core (Fig. 1). Let (J,K) be a point on the computational mesh and (JJ,KK) the corresponding point in core. Let each record be the Jth line with the number of words in the record given by

$$K = 1,IST$$

If there are NST records per block, then these are NIST words per block,

$$NIST = NST \times IST$$

Theory (Cont'd)

The solution algorithm requires overlapping blocks as shown on Fig. 10. Hence we have the block number

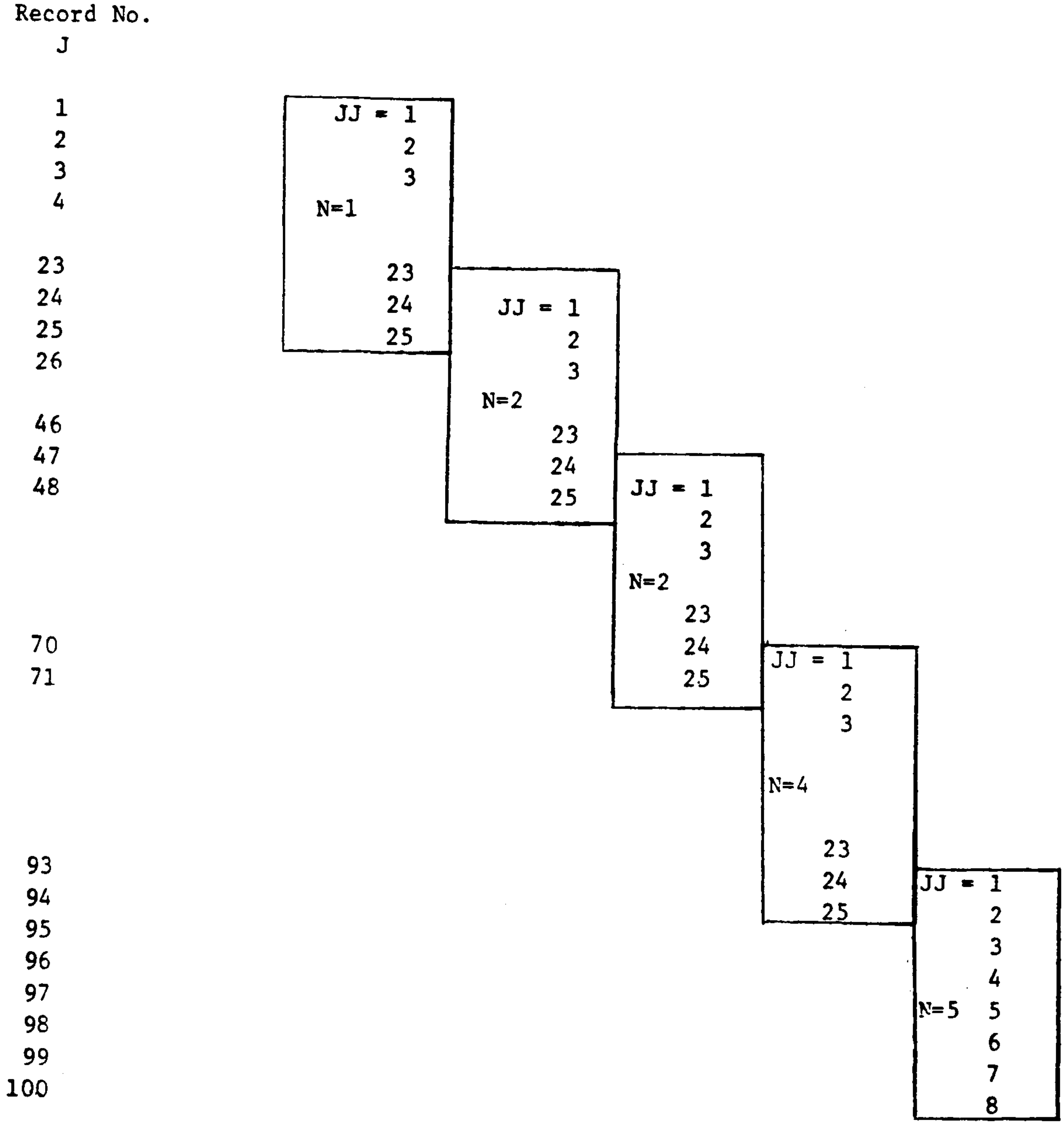
$$N = (J-2)/(NST-2) + 1$$

and the JJ point in core is given by

$$JJ + J-(N-1) \times (NST-2)$$

This subroutine is coded so that a new block is ready only when N = NL.

FIG.10 I/O for Streamline Curvature Solution
Overlapping Blocks



Subroutine READPG(J,JJ)

Object

Read variable for curvature calculation

Options

None

List of Symbols

J	= J	,Record number
JJ	= JJ	,Record number in block N
N		,Block number
G		,Streamline coordinate data (see COMMON/SPCFD/)
P		,Stream function
NST	= 25	,Number of records per block
NBK		,Number of words to move pointer
NIST		,Number of words per P block
NGDRM	= 25	,Unit number of G array
NPDRM	= 24	,Unit number for P array
NL		,Last P block number
NBIST		,No. words for 2 P records
NGIST		,No. words for 2 G records
NGL		,Last G record number

Theory

This subroutine reads the P file according to Subroutine READPF but reads only the Jth G record which is kept in core.

Subroutine RECØRD (ARG. LIST)

Object

Calculate record numbers

Options

IØPT14 = 0 , KDX = 1

> 0 , KDX > 1

JRECFI > NØPT7 , JRECFI = NØPT7

JRECFV > NØPT8 , JRECFV = NØPT8

List of Symbols

J	,	Jth coordinate station
JRECFI	,	Corresponding inviscid flow record number
JRECFV	,	Corresponding viscous flow record number
NFI	,	Index inviscid flow
NFV	,	Index viscous flow
NØPT7	,	No. records on unit MDRUM
NØPT8	,	No. records on unit NDRUM

Theory

See Section 5.5

Subroutine REDINP

Object

Read input parameters and variables

Options

Data cards are read according to input options
IØPTN where N = 1,17.

List of Symbols

Common block variables

Theory

This subroutine reads all input variables

Function RØBRTS(C,ETA,LØP)

Object

Compute distorted mesh using Roberts' transformation

Options

LØP = 0 Wall - wall boundary
    = 1 Wall-free stream boundary
    =-1 Free stream-wall boundary

List of Symbols

C	=	C	,Distortion parameter
ETA	=	η	,Input variable (uniform mesh)
LØP	=		,Option

Output Variable

RØBRTS = n ,Output variable

Theory

The Roberts' transformation for a distorted mesh on both sides is given by

$$n' = \frac{(c+1/2)\exp\left[2\ln\left(\frac{c+1/2}{c-1/2}\right)\left(\eta'-1/2\right)\right] - (c-1/2}{1+\exp\left[2\ln\left(\frac{c+1/2}{c-1/2}\right)\left(\eta'-1/2\right)\right]} \tag{1}$$

where

$$0 \le \eta' \le 1.0 \qquad 0 \le n' \le 1.0 \tag{2}$$

For the different options we have

$$\left.\begin{array}{l} \eta' = \eta \\ n = n' \end{array}\right\} L\emptyset P = 0 \tag{3}$$

$$\left.\begin{array}{l} \eta' = \eta/2 \\ n = 2n' \end{array}\right\} L\emptyset P = 1 \tag{4}$$

$$\left.\begin{array}{l} \eta' = (1+\eta)/2 \\ n = 2n' - 1 \end{array}\right\} L\emptyset P = -1 \tag{5}$$

Subroutine SCURVA (IDBU,KHØLD)

Object

Calculate curvature from potential flow solution

Options

IDBU = 0 Update density
> 0 Print SCURVA solution, update curvature

Variables

KHØLD		,No. ADD code streamlines
KL		,No. SCURVA streamlines
Q(J,K)		,Coordinate functions
P(K)	ψ_k^J	,Stream function a station J (dimensionless)
G(K)	G	,Coefficient for velocity calculation
R(K)	P	,Density Ratio (P/P_r) (dimensionless)
US	U_s	,Streamwise velocity (dimensionless)
UN	U_n	,Normal velocity (dimensionless)
U	U	,Total velocity (dimensionless)
COSTH	$\cos^2(\theta)$	,$(\text{Cosine})^2$ of flow angle θ
CURV	$\frac{\partial V}{\partial n}$	,Curvature of streamline (dimensionless)

Theory

Once the potential flow solution has been obtained from subroutine PØIS, this subroutine will calculate the flow angle and streamline curvature according to Ref. (1).

References

1. Anderson, O.L. and D. E. Edwards, Extension to an Analysis of Turbulent Swirling Compressible Flow in Asixymmetric Ducts, NASA Contract No. NAS3-21851, 1981, UTRC Report R81-914720.

Subroutine SLETE

Object

Find indices for strut control surfaces

Options

If IØPT2 = 0, JLEDG = JTEDG = 101

List of Symbols

RHLE, ZHLE	=	R_{HLE}, Z_{HLE}, Coordinate hub leading edge (dimensionless)
RHTE, ZHTE	=	R_{HTE}, Z_{HTE}, Coordinate of hub trailing edge (dimensionless)
RHLE, ZTLE	=	R_{TLE}, Z_{TLE}, Coordinate of tip leading edge (dimensionless)
RTTE, ZTTE	=	R_{TTE}, Z_{TTE}, Coordinate of tip trailing edge (dimensionless)

Theory

The projection of the blade onto the (R,Z) plane is determined by calculating the coordinate points of the four corners of the blade using subroutines TRLETE, TRBLDE. Then a straight line is drawn connecting the leading edge points and a straight line connecting the trailing edge points is drawn. Subroutine ALINE is used to determine the intersections of the leading and trailing edges with the walls. For a unique solution, these four points must lie outside the duct. Then JLEDG is the station just upstream of the leading edge and JTEDG is the station just downstream of the blade.

Subroutine SLØTA (LØP)

Object

Construct duct with slots

Options

ENTRY SLØTA

LOP	= 1	Read slot parameters
	= 2	Construct walls with all slots
	= 3	Normalize slot variables
	= 4	Arrange slots in order of S
	= 5	Write slot input data

ENTRY SLØTGD (NØPT)

Construct NØPT'th slot

List of Symbols

CSN	$= \cos\theta_w$	, Cosine of wall angle
DRSLØT	$= H\cos\theta_w$	, Increment in slot height (dimensionless)
DZ	$= \Delta Z$	, Increment in axial distance (dimensionless)
SHUB,STIP	$= S_H, S_T$	, S coordinate location of slot
ZHUB,ZTIP	$= Z_H, Z_T$	, Axial location of walls (dimensionless)
ZZHUB,ZZTZP	$= Z_{ZH}, Z_{ZT}$	, Axial location of slots (dimensionless)
ZZ	$= Z_{SL}$	, Axial location NØPT'th slot (dimensionless)

Theory

A duct without slots is constructed on the first pass. Then on successive passes $H\cos\theta_w$ is added according to Fig. 11.

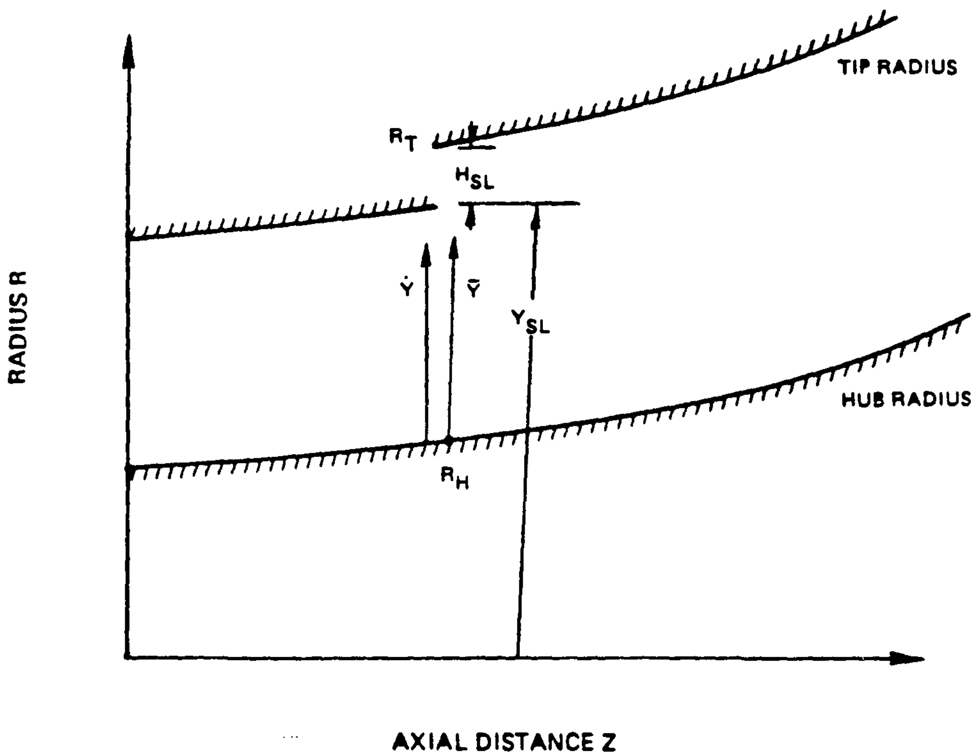


FIG. 11. INTERPOLATION OF FLOW AT SLOT LOCATION

Subroutine SLTFLØ(LØP)

Object

Compute slot inlet flow

Options

LØP= Slot index

List of Symbols

ALST	$= \alpha_{SLT}$	, Slot injection swirl angle (rad)
AMINF	$= M_\infty$	, Slot injection Mach number (dimensionless)
AMUI	$= \mu_\infty/\mu_r$	, Freestream viscosity (dimensionless)
AN	$= n$	, Boundary layer power law (1/7)
ANUW	$= \nu$	, Wall kinematic viscosity (1/sec)
A2CF	$= 2C_f$	, Wall friction coefficient (dimensionless)
CCMH	$= 2.2/\kappa$	, Constant for universal velocity (dimensionless)
DEL	$= \delta$	, Boundary layer thickness (ft)
DELS	$= \delta^*$	, Boundary layer displacement thickness (ft)
DELT	$= \Delta$	, Boundary layer thickness (dimensionless)
DSTR	$= \Delta^*$	, Boundary layer thickness (dimensionless)
DWFLØ	$= \mathring{W}_{SL}$	, Weight flow in slot (dimensionless)
DWFLØ1	$= \mathring{W}_{SL}$	, Weight flow in slot (lb/sec)
HSLT	$= H_{SL}$	, Slot height (dimensionless)
H12	$= H_{12}$	, Boundary layer form factor (δ^*/θ)
POINF	$= \Pi_\infty$	, Total pressure slot flow (dimensionless)
RETH	$= Re_\theta$	, Reynolds number, momentum thickness (dimensionless)
RHUB	$= R_H$	, Hub radius (dimensionless)
RØINF	$= \rho_\infty$	, Freestream density (dimensionless)

RØW	$= P_W$	, Wall density (dimensionless)
RTIP	$= R_T$	, Tip wall radius (dimensionless)
SIGW	$= \Sigma_W$	, Wall stress (dimensionless)
TINF	$= \Theta_\infty$	, Freestream temperature (dimensionless)
TW	$= \Theta_W$	, Wall temperature (dimensionless)
TOINF	$= \Theta_\infty$	, Freestream total temperature (dimensionless)
U	$= U$	, Magnitude of velocity (dimensionless)
UIN	$= u$	, Magnitude of velocity (ft/sec)
UINF	$= u_\infty$	, Freestream velocity (ft/sec)
USW	$= U^*$	, Wall friction velocity (ft/sec)
WFLØ1	$= \mathring{W}_1$	, Weight flow upstream of slot (dimensionless)
WFLØ2	$= \mathring{W}_2$	, Weight flow downstream of slot (dimensionless)
Y	$= Y$	, Distance from wall (dimensionless)
YBAR	$= \bar{Y}$	, Distance from wall (dimensionless)
YMID	$= Y_m$	, Midpoint of slot (dimensionless)
YPLUS	$= Y^+$	, Universal distance (dimensionless)
YSLØT	$= Y_{SL}$	, Distance to slot lip (dimensionless)

Theory

The flow at the slot station is computed in two parts. First, the known upstream flow from the old Y grid is interpolated to the new $\bar{Y}$ grid from $R_H \leq \bar{Y} \leq Y_{SL}$. In the second step, the flow entering through the slot is computed for $Y_{SL} \leq \bar{Y} \leq R_T$. Since the total pressure and total temperature of the slot flow is given, and the static pressure inside the duct has been computed, the Mach number of the slot inlet flow can be computed.

$$M_\infty = \left\{ \frac{2}{\gamma - 1} \left[\left(\frac{\Pi_{0\infty}}{\Pi_\infty} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] \right\}^{1/2} \tag{1}$$

Then the remaining freestream properties are

$$\Theta_\infty = \Theta_{0\infty} \Big/ \left(1 + \frac{\gamma - 1}{2} M_\infty^2 \right) \tag{2}$$

$$P_\infty = \Theta_\infty / \pi_\infty \tag{3}$$

$$U_\infty = M_\infty / M_r / \sqrt{\Theta_\infty} \tag{4}$$

The slot flow is assumed to be fully-developed, hence

$$\Delta = H/2 \tag{5}$$

$$\Delta^* = \Delta / (1 + 7) \tag{6}$$

Coles' velocity profile is assumed, and a friction velocity based on Coles' profiles is computed using Function UCØLES. Then, the velocity is given by

$$U = \frac{u^*}{u_r} f(|Y|, Y^+, \delta) \tag{7}$$

$$\Theta = \Theta_\infty \left\{ 1 + P_r^{1/3} \frac{\gamma - 1}{2} M_\infty^2 \left[1 - \left(\frac{U}{U_\infty} \right)^2 \right] \right\} \tag{8}$$

Subroutine SMØØTH (X,Y,JX,XB,YB,JXB,JXK)

Object

Least squares spline fit

Options

None

List of Symbols

A(I), B(I)	$= a_I, b_I$	, Constants of integration
CK(I,J)	$= c_{I,J}$	, Spline coefficients
JX		, Number of input points
JXB		, Number of output points
JXK		, Number of spline nodes
X(J), Y(J)	$= X, Y$	, Input curve
X(I), Y(I)	$= \bar{X}, \bar{Y}$	, Output curve
YPP(J)	$= Y''$	, Second derivative input curve
XK(I), YK(I)	$= \hat{X}, \hat{Y}''$	, Node locations

Theory

The input curve is numerically differentiated to obtain the second derivative of Y(X). JXK equally spaced nodal points are assumed including the end points. The ISML routine returns spline coefficients of the form

$$\bar{Y}_J'' = c_{I,3} \cdot D^3 + c_{I,2} D^2 + c_{I,1} D + \hat{Y}_I'' \tag{1}$$

where

$$\bar{D} = X_J - \hat{X}_I \tag{2}$$

Equation (1) is integrated algebraically to obtain

$$\bar{Y}_J = \frac{C_{I,3}}{20} D^5 + \frac{C_{I,2}}{12} D^4 + \frac{C_{I,1}}{6} D^3 + \frac{\hat{Y}_I''}{2} D^2 + A_I D + B_I + Y_I \tag{3}$$

with the boundary condition that the end points of the curve remain unchanged.

Subroutine SØLVI

Object

Integrate equations of motion

Options

ALPHAK	= 1.0	Include convection terms
	= 0.	Reyhner, Flugge-Lotz approximation
BETAH	= 0.	Forward differences for convection
	= 1.0	Backward differences for convection
IDBG5	= 0	No debugging printout
	= 1	Debug printout of viscous solution
IDBG8	= 0	No debug printout
	= 1	Debug of matrix inversion algorithm
IDBG14	= 0	No debug printout
	= 1	Debug printout of slot injection
IFLAG		Used with IDBG8
IFSTEP	= 1	Test for optimum step size
	= 2	Do not test for optimum step size
IGDUM	= 0	Algebraic turbulence model when IØPT12 = 3
	> 0	Two equation turbulence model
IVTEST	= 0	Do not print solution
	= 1	Print solution every station for separated flow
IØPT11	= 0	OD wall boundary condition
	= 1	OD freestream boundary condition

IØPT12	= 0,1,2	Algebraic turbulence models
	= 3	Two equation turbulence models
IØTP13	= 0	No slots
	= 1	Slots
IØPT14	= 0	No global iteration for separated flow
	= 1	Global iteration for separated flow
IØPT15	> 0	Start calculation at station IØPT15
IØPT16	> 0	End calculation at station IØPT16
IØPT17	= 0	No restart
	> 0	Restart calculation at station IØPT17
NØPT1	= 0	First station setup flow parameters
	= 1	First calculated station
	= 2	Continue calculation
NØTP2	= 1	Adiabatic wall
	= 2	Nonadiabatic wall
NØTP4	= 1	ID wall boundary condition
	= 2	ID axis of symmetry boundary condition
NØPT5	= 0	No fatal errors
	> 0	Fatal error stop calculation

List of Symbols

AA(I,J)	$= a_{IJ}$	, Element of $\bar{\bar{A}}$ matrix
AB(I,J)	$= b_{IJ}$	, Element of $\bar{\bar{B}}$ matrix
AC(I,J)	$= c_{IJ}$	, Element of $\bar{\bar{C}}$ matrix

List of Symbols (Cont'd)

AD(I,J)	$= d_{I,J}$	, Element of $\bar{\bar{D}}$ matrix
ADI(I,J)	$= d^{-1}_{IJ}$	, Element of $\bar{\bar{D}}^{-1}$ matrix
AE(I,J,K)	$= e_{IJ}$	, Element of $\bar{\bar{E}}$ matrix
AQ(I)	$= q_I$	, Element of $\bar{Q}$ vector
AZ(I,K)	$= z_I$	, Element of $\bar{Z}$ vector
BA(I,K)	$= \left(\frac{D\Delta}{Dt}\right)^{J-2+I}$	, Entropy increase when LL = 1
BA(I,K)	$= \left(\frac{D\Delta_o}{Dt}\right)^{J-2+I}_K$	, Total temperature increase when LL = 2
DDSTAR = $A\delta^* = (\delta^{*J} - \delta^{*J-1})/\delta^{*J-1}$		, Change in δ^*
DDSTRM	$= (\Delta\delta^*)_M$	, Minimum change in δ^*
DELØR	$= (\Delta X/\delta^*)_M$	, Maximum step size
DSIG = $\Delta\Sigma = (\Sigma^J_w - \Sigma^{J-1}_w)/\Sigma^{J-1}_w$		, Change in wall stress
DSIGM	$= (\Delta\Sigma)_M$	, Maximum change in wall stress
DSTAR	$= \delta^*$	, Displacement thickness
EENTP	$= \varepsilon(\ )$	, Truncation errors in
EPRES	$= \varepsilon(\Pi)$	, Truncation error in Π
ERØTH	$= \varepsilon(\ \ )$	, Truncation error in
ERØUS	$= \varepsilon(\ U_s)$	, Truncation error in $(\ U_s)$
EUSUS	$= \varepsilon(U_s^2)$	, Truncation error in (U_s^2)
EUSUSM	$= \varepsilon(U_s^2)_M$	, Maximum error in (U_s^2)
EUPUP	$= \varepsilon(U_\phi^2)$	, Truncation error in (U_ϕ^2)
FVJ(I,J,K)	$= F(I,J,K)^{\nu-1}$	, Dependent variables previous global iteration
FV(I,K) = FVJ(I,J+1,K)$^{\nu-1}$		, Dependent variables backward differencing
JJ		, Coarse grid station counter

JKDS		, Fine grid station counter
ENREF	$= \bar{I}_1$	, Reference entropy for Mach transformation
PIREF	$= \bar{\Pi}_1$	, Reference pressure for Mach transformation
THREF	$= \bar{\Theta}_1$	, Reference temperature Mach transformation

Theory

Solution Algorithm

The equations of motion are described in Ref. 1. Details of the finite difference equations and the solution algorithm using the method of block tridiagonal factorization is described in Ref. 2. The programmer may refer to Table I for the definition of rows and columns in the diagonal block. A description of the global iteration scheme for treating separated flow is given in Ref. 3.

Truncation Errors

The truncation errors calculated in this subroutine are those associated with linearizing the equations of motion by expansion in a Taylor series (see Ref. 2). Then for any two variables A and B we have

$$\epsilon(AB) = \frac{(AB)^J - \left[A^J \; B^{J-1} + A^{J-1} \; B^J - (AB)^{II}\right]}{(\bar{A}\bar{B})^J} \tag{1}$$

where $\bar{A}$ and $\bar{B}$ are mass flow weighted averages.

Step Size Algorithm

The controlling factor in the selection of the streamwise step size is the thickness of the boundary layer rather than the length of the duct. Practical experience has demonstrated that the streamwise step size should be of the order of magnitude of the boundary layer thickness. In some cases, for highly curved walls, the radius of curvature of the wall may be a controlling factor. Since wall stress was found to be a sensitive indicator of wall curvature, a criteria based on the rate of change of wall stress was developed. In addition to these factors, the ADD code uses an analysis which linearizes the equations of motion using a Taylor series expansion. Therefore, a third factor controlling the step size is this truncation error which should be kept below some maximum error. Finally, in certain cases, as equilibrium flow is approached, the boundary layer thickness grows slowly and the step size may be increased.

The ADD code uses a fine grid interpolated from a coarse grid. Whereas the coarse grid is determined by the JL mesh points required to solve the potential flow through the duct, the fine grid (JLXKDS) is determined by the number of mesh points required by the boundary layer solution. At each grid point on the coarse mesh, the automatic step size algorithm calculates the fine grid parameter KDS using the criteria

$$\frac{X_{J+1}-X_J}{KDS} = \delta^* \left(\frac{\Delta X}{\delta^*}\right)_M \tag{2}$$

where the J indices indicates the coarse grid step size. One integration step is taken and the following checks are made:

$$\Delta\Sigma < (\Delta\Sigma)_M \tag{3}$$

$$\epsilon(U_S^2) < \epsilon(U_S^2)_M \tag{4}$$

If these conditions are satisfied, the integration continues for the KDS steps. If these conditions are not satisfied, KDS is doubled and the first integration step is repeated. This process is continued until conditions (3) and (4) are satisfied. If KDS is doubled, IFSTL times the calculation is terminated.

For cases approaching equilibrium flow

$$\text{If } \Delta\delta^* < (\Delta\delta^*)_M \text{, then } (\Delta X/\delta^*)_M = 100 \tag{5}$$

and a much larger step size may be taken.

Work-Loss Calculation

Duct flow calculations require accurate determination of the work input and viscous losses. This subroutine integrates the following equations along a viscous flow streamline ψ = constant with the right hand side known,

$$\frac{D(\Delta\Theta_0)}{Dt} = (\gamma - 1)\, M_r^2\, V_B\, H_\phi/P \tag{6}$$

$$\frac{D(\Delta I)}{Dt} = \frac{\gamma M_r^2}{\Pi}\left[\frac{(\Sigma_{ns}^2 + \Sigma_{n\phi}^2)}{(\mu_E/\mu_r)} Re_r + \Phi_B\right] \tag{7}$$

where $\Delta\theta_0$ is the incremental work input produced by the blades, and ΔI is the incremental entropy rise due to viscous dissipation.

References

1. Anderson, O. L.: Calculation of Internal Viscous Flows in Axisymmetric Ducts at Moderate to High Reynolds Numbers. Int. J. of Computers and Fluids, Vol. 8, No. 4, pp. 391-411, December 1980.

2. Anderson, O. L.: User's Manual for a Finite Difference Calculation of Turbulent Swirling Flow in Axisymmetric Ducts with Slot Cooled Walls. Vols. I & II, USAAMRDL-TR-74-50, 1974.

3. Anderson, O. L. and D. E. Edwards: Extensions to an Analysis of Turbulent Swirling Compressible Flow in Axisymmetric Ducts. UTRC Report R81-914720-18, 1981.

TABLE I MATRIX ELEMENTS AA(IVAR,IEQ)

Col. IVAR	Variable	Row IEQ	Equation
1	Ψ	1	Heat flux equation
2	U_s	2	Equation state
3	U_ϕ	3	S momentum equation
4	Π	4	ϕ momentum equation
5	I	5	Energy equation
6	Θ	6	Continuity equation
7	P	7	Σ_{ns} stress equation
8	Σ_{ns}	8	$\Sigma_{n\phi}$ stress equation
9	$\Sigma_{n\phi}$	9	N momentum equation
10	Q	10	Entropy equation

Subroutine STRESI (LØP)

Object

Calculate initial stress and heat flux

Options

LØP = 1	Calculate F(L,2,K)	L = 8, 10
= 2	Calculate F(L,1,K)	1 = 8, 10
IØPT17 = 0	Initialize stress at first station	
> 0	Calculate turbulent viscosity only	

List of Symbols

See CØMMØN BLØCK variables

Theory

With the velocity distribution, turbulent viscosity, and turbulent conductivity known, the stress and heat flux can be calculated using the algebraic turbulence model described in Ref. 1. In addition, the total temperature and total pressure at the initial station are calculated for use by the work and loss calculation in subroutine SØLVI.

References

1. Anderson, O. L. and D. E. Edwards: Extensions to an Analysis of Turbulent Swirling Compressible Flow in Axisymmetric Ducts. UTRC Report R81-914720-18, February 1981.

Subroutine SUBLAY (AK, AP, Y, Q, EPS)

Object

Initializes k, t turbulence model in inner layer

Options

None

List of Symbols

AK	κ	, von Karman constant
AP	A^+	, von Driest constant
Y	Y^+	, Universal coordinate $(\rho_w u^* / \mu_w)$
Q	K^+	, Universal kinetic energy (k/u^{*2})
EPS	ε^+	, Universal dissipation $(\mu/\rho\varepsilon/u^{*4})$
AMUT	μ_T^+	, Universal turbulent viscosity (μ_T/μ_w)

Theory

This subroutine initializes k and ε in the inner region of the boundary layer by determining first the turbulent viscosity through the van Driest wall function and then determining the kinetic energy and dissipation through the relations described in Reference 1.

References

Anderson, O. L. and D. E. Edwards, Extension to an Analysis of Turbulent Swirling Compressible Flow in Axisymmetric Ducts. NASA Contract NAS3-21853, 1981, UTRC Report T81-914720.

Subroutine TPRINT (JNUM)

Object

Print CPU time

Options

ITIME	= 0	Initialize time
	$\neq 0$	Continue time

List of Symbols

JNUM , Not used

Theory

This is a dummy subroutine which calls UNIVAC time routine SUPS.

Subroutine TRBLDE (X,Y,RP,ZP)

Object

Transformation from stacking plane to duct plane

Options

None

List of Symbols

RCLO, ZCLO	= R_{CLO}, Z_{CLO}	, Origin of stacking plane (dimensionless)
RP, ZP	= R, Z	, Coordinates in duct plane (dimensionless)
THCL	= θ_{CL}	, Rotation of stacking plane (deg)
X,Y	= X,Y	, Coordinates in stacking plane (dimensionless)

Theory

The transform from the stacking plane to the duct plane is given by

$$R = R_{CLO} + Y \cos\theta_{CL} + X \sin\theta_{CL} \tag{1}$$

$$Z = Z_{CLO} + X \cos\theta_{CL} - Y \sin\theta_{CL} \tag{2}$$

Subroutine TRLETE (KK,XLE,YLE,XTE,YTE)

Object

Find leading and trailing edge in stacking plane

Options

None

List of Symbols

ALP	α	, Stagger angle (deg)
CØRD	C	, Chord (dimensionless)
XCL, YCL	$= X_{CL}, Y_{CL}$	, Coordinates of centerline (dimensionless)
XLE, YLE	$= X_{LE}, Y_{LE}$	, Coordinates of leading edge (dimensionless)
XTE, YTE	$= X_{TE}, Y_{TE}$	, Coordinates of trailing edge (dimensionless)

Theory

The projection of the blade to the (r, Z) plane is

$$X_{LE} = X_{CL} - 1/2\ C \cos(\alpha) \tag{1}$$

$$Y_{LE} = Y_{CL} \tag{2}$$

$$X_{TE} = X_{CL} + 1/2\ C \cos(\alpha) \tag{3}$$

$$Y_{TE} = Y_{CL} \tag{4}$$

Subroutine TURB

Object

Compute turbulent viscosity using algebraic turbulence model.

Options

IOPT12 = 0	Original eddy viscosity model
= 1	Eddy viscosity model with low Reynolds number corrections (not tested)
= 2	Eddy viscosity model with curvature corrections

List of Symbols

AMUE	$= \mu_E/\mu_r$	,Effective viscosity (dimensionless)
AMUER(K)	$= (\mu_{T\infty}/\mu_r)$	,Freestream turbulent viscosity (dimensionless)
AMUM	$= \mu_\infty/\mu_r$	,Freestream molecular viscosity (dimensionless)
AMUW	$= \mu_w/\mu_r$	,Wall value of molecular viscosity (dimensionless)
AMUWK	$= (\mu/\mu_r)_{K+\frac{1}{2}}$	,Molecular viscosity (dimensionless)
AMUO	$= (\mu_{T\infty}/\mu_r)$	,Maximum freestream viscosity (dimensionless)
BETAC	$= \beta_s$	,Eide & Johnston coefficient (6.)
BETAD	$= \beta_\phi$	,Eide & Johnston coefficient (6.)
BETAPB	$= \alpha_\phi$	,Bradshaw coefficient (6.)
BETASB	$= \alpha_s$	,Bradshaw coefficient (0.)
DELO	$= \Delta^*$	,Displacement thickness (dimensionless)
DU	$= \Delta u$	,Velocity finite-difference (dimensionless)
DUDZ	$= dU/dZ$	,Velocity derivative (dimensionless)
E	$= E$	,Rate of strain (dimensionless)
EM	$= E_\infty$	,Strain freestream (dimensionless)

Variables (Cont'd)

EMH, EM_T	$= E_{\infty H}, E_{\infty T}$	,Strain hub, tip, edge of inner layer (dimensionless)
ENP	$= E_{n\phi}$	,Swirl rate of strain (dimensionless)
ENS	$= E_{ns}$	,Streamwise rate of strain (dimensionless)
EW	$= E_w$	,Wall rate of strain (dimensionless)
FCURV	$= F$	Curvature correction to eddy viscosity
PHI	$= \phi$	,Integrand (dimensionless)
RHOM	$= \rho_{\infty}$	,Density freestream (dimensionless)
RC	$= R_{i_c}$	,Streamwise component of Richardson Number
RICPB	$= R_{i_c}$	,Tangential component of bulk Richardson number
RICSB	$= R_{i_\phi}$	,Streamwise component of bulk Richardson number
RP	$= R_{i_\phi}$	,Tangential component of Richardson number
SIGWH	$= \Sigma_{wh}$	,Wall stress hub (dimensionless)
SIGWK	$= \Sigma_{wk}$	,Wall stress inner layer (dimensionless)
SIGWT	$= \Sigma_{wt}$	,Wall stress tip (dimensionless)
TPLUS1, TPLUS2	$= T_1^+, T_2^+$	,Universal wall stress (dimensionless) (τ/τ_w)
UK(K)	$= U_K$	,Magnitude of velocity (dimensionless)
UM	$= U_\infty$	,Freestream velocity (dimensionless)
USTARH, USTART	$= U_H^*, U_T^*$	,Friction velocity hub, tip (dimensionless)
Y	$= Y$	,Distance across duct (dimensionless)
YK	$= Y_{k+\frac{1}{2}}$	,Distance across duct (dimensionless)

Variables (Cont'd)

YMH,YMT	$= Y_H, Y_T$	,Distance to inner layer hub, tip (dimensionless)
YPLUS1, YPLUS2	$= Y_1^+, Y_2^+$	,Universal distance (dimensionless)

Theory

The algebraic turbulence models are described in Ref. 1.

References

1. Anderson, O.L. and D.E. Edwards, Extension to an Analysis of Turbulent Swirling Compressible Flow in Axisymmetric Ducts, NASA Contract No. NAS3-21853, 1981, UTRC Report T81-914720.

Subroutine TURB2Q

Object

Calculate turbulent viscosity using k, E turbulence model.

Options

NTURB2 = 0	Set up initial conditions
$\neq$ 0	Calculate 2-equation turbulence model
IØPT17	Restart capabilities, IOPT17>0 calculation

List of Symbols

DHF(1,r)		,Not used
DHF(2,K)	$= (\mu_E/\mu_r)^J$	,Effective Viscosity
DPF(1,K)		,Not used
DPF(2,K)	$\frac{1}{P_{R_T}} (\mu_E/\mu_r)^J$	,Effective thermal conductivity
TRB(1,1,K)	K_K^{J-1}	,Turbulence kinetic energy, (k/u_r^2)
TRB(1,2,K)	K_K^J	,Turbulence kinetic energy (k/u_r^2)
TRB(1,2,K)	$(K_K^J)^{\nu-1}$	,Turbulence kinetic energy (k/u_r^2)
WRELAX	ω	,Relaxation parameter (.5)
ITMAX		,Maximum number of iterations (100)
TRB(2,1,K)	E_K^{J-1}	,Turbulence dissipation $(\rho_r/\mu_r \ (\frac{r_r}{u_r})^2 \varepsilon\ )$
TRB(2,2,K)	E_K^J	,Turbulence dissipation $(\rho_r/\mu_r \ (\frac{r_r}{u_r})^2 \varepsilon\ )$
TRB(2,3,K)	$(E_K)^{\nu-1}$	,Turbulence dissipation $(\rho_r/\mu_r \ (\frac{r_r}{u_r})^2 \varepsilon\ )$
AMUL(K)	μ_K^{J-1}/μ_r	,Molecular viscosity
AMUT(K)	$\mu_{T_K}^{J-1}/\mu_r$	,Turbulent viscosity
AMUE(K)	$(\mu_E/\mu_r)_K^{J-1}$	,Effective viscosity

List of Symbols (Cont'd)

E(K),FM(K)	= E_K, F_K	,Matrix solver
TP(K)	= P_K^J	,Turbulence production (dimensionless)
TRE(K)	= R_{EK}^{J-1}	,Turbulence Reynolds number
TRJ(K)	= R_{itK}^{J-1}	,Richardson number
CDAMP	=	,.0115
C1	= C_1	,1.35
SIGE	= σ_E	,1.3
SIGK	= σ_K	,1.0
CMUO	= C_μ	,.09
CMU	= C_μ	,$.09*\ 1-e^{(-CDAMP*Y^+)}$
C2	= C_2	,$1.8*\ 1.-\frac{.4}{1.8} * e^{-R_t{}^{2}/36}\ (1-.2\ R_{i_t})$
C3	= C_3	e^{-5Y^+}
YP1US	= Y^+	,Universal distance
SK(1,K)	= S_{B_K}	
SB(2,K)	= S_{B_E}	
SD(1,K)	= S_{D_K}	
SD(2,K)	= S_{D_E}	
GAM(L,K)	= Γ_K	,$\mu+\mu_T/\sigma_K$
GAM(2,K)	= Γ_E	,$\mu+\mu_T/\sigma_E$
TURBIF	= $\overline{u'u'}/\overline{u}^2$	,Freestream turbulence (not tested)

List of Symbols (Cont'd)

QPLUS		,Universal turbulent kinetic energy $\overline{u'u'}/(u*)^2$
EPS	E^+	,Universal turbulent dissipation
ERRREY		,Relative change in R per iteration
ERRREM		,Error tolerance (.001)
AKINF	K_∞	,Freestream turbulence kinetic energy (not tested) $\sqrt{\overline{u'u'}/\overline{u}^2}$
EINF	E_∞	,Freestream turbulence dissipation (not tested)
UINF	U_∞	,Freestream velocity

Theory

The two-equation turbulence model of Chien is solved using the method described in Ref. (1).

References

1. Anderson, O.L. and D.E. Edwards, Extension to an Analysis of Turbulent Swirling Compressible Flow in Axisymmetric Ducts, NASA Contract No. NAS3-21853, 1981, UTRC Report T81-914720.

Function UBLAS(Y)

Object

Calculate Blasius velocity profile

Options

None

List of Symbols

UBLAS = u/u_∞ , Velocity ratio

Y = y/δ , Distance from wall

Theory

The Blasius velocity profile is linearly interpolated from a table of values given in Ref. 2.

Reference

1. Schlicting, H.: Boundary Layer Theory. 6th Ed., McGraw Hill, N.Y., 1968.

Subroutine UMACH (PT, TT, P, U)

Object

Calculate inviscid velocity

Options

None

List of Symbols

P	P/P_r	, Static pressure (dimensionless)
PT	P_T/P_r	, Total pressure (dimensionless)
TT	T_T/T_r	, Total temperature (dimensionless)
U	U/U_r	, Velocity (dimensionless)

Theory

The inviscid velocity U is calculated from the input P, PT, TT using the isentropic flow relations.

Subroutine VARFUN (JINDEX, INDEX, MINDEX)

Object

Store variables to be used by PRTØUT

Options

None

Input Variables

JINDEX	Index of streamwise station
INDEX	Index of viscous flow quantities
MINDEX	Index of effective viscosity
F	Viscous flow array
Q	Geometry flow array
KL	Number of streamwise stations

Output Variables

VARBL(1,J,K)	ψ	, Stream function (dimensionless)
VARBL(2,J,K)	U_s	, Streamwise velocity (dimensionless)
VARBL(3,J,K)	U_ϕ	, Swirl velocity (dimensionless)
VARBL(4,J,K)	P	, Density (dimensionless)
VARBL(5,J,K)	Σ_{ns}	, Streamwise stress (dimensionless)
VARBL(6,J,K)	$\frac{\mu_E}{\mu_r}$	. Effective viscosity
VARBL(7,J,K)	R	, Radius (dimensionless)
VARBL(8,J,K)	Z	, Axial distance (dimensionless)
VARBL(9,J,K)	V	, Metric scale coefficient (dimensionless)

Output Variables (Cont'd)

VARBL(10,J,K)	G	,	Gap (dimensionless)
VARBL(11,J,K)	$\frac{\partial R}{\partial S}$	,	Streamwise derivative of radius
VARBL(12,J,K)	$\frac{\partial V}{\partial N}$	,	Curvature of potential line
VARBL(13,J,K)	$\frac{\partial V}{\partial S}$	,	Curvature of stream line
VARBL(14,J,K)	y/h	,	Fractional distance across duct

Theory

Module PRTØUT requires information from three streamwise stations in order to perform the differencing of differential equations. This subroutine stores the information required in array VARBL.

Subroutine WBLEED

Object

Calculate perforated wall bleed

Options

IØPT18	= 0	No wall bleed
	= 1	Tip wall bleed
	= 2	Hub wall bleed
	= 3	Tip/hub wall bleed
PCHEK	> 1.0	Flow enters tunnel
	< 1.0	Flow leaves tunnel

Input Variables

AHAS	$= A_h/A_s$	Ratio of hole area to surface area
CDISH	$= C$	Discharge coefficient
PTP	$= P_{TP}$	Plenum total pressure
TTP	$= T_T$	Plenum total temperature

Internal Variables

AMTU	$= M_{TU}$	Tunnel Mach number
GAMMA	$= \gamma$	Ratio of specific heats
GASR	$= R$	Gas constant
PS	$= P$	Static pressure (psfa)
PT	$= P_T$	Total pressure (psfa)
PSTU	$= P_{TU}$	Tunnel static pressure (psfa)
PTTU	$= P_{TTU}$	Tunnel total pressure (psfa)
TSTU	$= T_{TU}$	Tunnel static temperature (deg R)
TTTU	$= T_{TTU}$	Tunnel total temperature (deg R)
RHØR	$= \rho_r$	Reference density (slug/ft^3)
USR	$= u_r$	Reference velocity (ft/sec)
PRESR	$= P_r$	Reference pressure (psfa)

Internal Variables (Cont'd)

TEMPR	$= T_r$	Reference temperature (deg R)
SGN	± 1	Sign convention

Output Variables

RH(9,J)	$= (\rho U_n)_H$	Mass bleed hub wall (slugs/ft^2/sec)
RT(9,J)	$= (\rho U_n)_T$	Mass bleed tip wall (slugs/ft^2/sec)

Theory

If one treats a single hole in a perforated wall as an orifice, then the mass flow can be derived in terms of the plenum stagnation conditions and the local static pressure inside the tunnel Holman (Ref. 1). Then an expression for the mass flow added to the tunnel flow is given by

$$(\rho U_n)_w = C \frac{A_h}{A_s} \frac{\gamma P_T}{\sqrt{\gamma \Re T_T}} \left(\frac{P_T}{P}\right)^{-\frac{1+\gamma}{2\gamma}} \left\{\frac{2}{\gamma-1}\left[\left(\frac{P_T}{P}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]\right\}^{1/2} \tag{1}$$

where P_T and T_T are the plenum conditions, P is the local tunnel static pressure, A_h/A_s is the ratio of the hole area to surface area, and C the effective discharge coefficient which is a property of the perforated wall. If the tunnel static pressure is greater than the plenum total pressure, the mass flow bleed is out of the tunnel. Under these conditions, P_T and T_T are taken from the wind tunnel conditions, and P is the plenum pressure which is assumed known.

The mass flow bleed is related to the stream function by

$$-\frac{\partial \Psi}{\partial s} = \frac{G}{V} \frac{(\rho u_n)_w}{\rho_r u_r} \tag{2}$$

Equations (1) and (2) provide the boundary condition for a perforated wall relating two dependent variables ψ and P in terms of the characteristics of the perforated wall and the plenum conditions.

The program checks the options according to the table below.

		O.D. Wall	I.D. Wall
$PCHEK = P_{TP}/P_{STU} > 1.0$ set	$P_T = P_{TP}$		
	$P = P_{STU}$	SGN = -1.0	+1.0
	$T_T = T_{TP}$		
$PCHEK = P_{TP}/P_{STU} < 1.0$ set	$P_T = P_{STU}$		
	$P = P_{TP}$	SGN = 1.0	-1.0
	$T_T = T_{STU}$		

<u>Reference</u>

1. Holman, J. P.: Experimental Methods for Engineers. McGraw-Hill Book Co., New York. 1966.

Subroutine WFITER

Object

Inlet weight flow iteration

Options

WFLI	= 0	No weight flow iteration
	> 0	Weight flow iteration
IØPT1	= 3,7	Iterate on Mach number
	= 4,8	Iterate on ID static pressure

List of Symbols

AMSI	= M^{ν}	Mach number
BINPUT(3,1,1)	= Π_H^{ν}	ID static pressure (P_H/P_r)
B311	= Π_H	Input ID static pressure (P_H/P_r)
EPRPIN	= ε_P	Error in normal pressure gradient
ERRW	= ε_w	Error in weight flow
IWFL1	= ν	Iteration counter
NØPT19	= ν	Iteration counter
WFLI	= w	Input weight flow (lb/sec)
WFLØ	= w^{ν}	Output weight flow (lb/sec)

Theory

Subroutine FLØWIN calculates an output weight flow WFLØ. This subroutine uses an iteration based on Newton's method to adjust the weight flow keeping the total pressure and total temperature fixed.

For IØPT1 = 3 or 7, the Mach number is varied using

$$M^{\nu+1} = M^{\nu} \, w/w^{\nu} \tag{1}$$

For IØPT1 = 4 or 8, the ID static pressure is varied

$$\Pi_H^{\nu+1} = \Pi_H^{\nu} + \left(\frac{d\Pi_H}{dw}\right)^{\nu} (w - w^{\nu}) \tag{2}$$

The error in weight flow is given by

$$\epsilon_w = |w - w^{\nu}|/w \qquad (3)$$

The error in normal pressure gradient is obtained from subroutine ERPIN.

Subroutine WRITEPF(JJ)

Object

Store updated potential flow solution.

Options

None

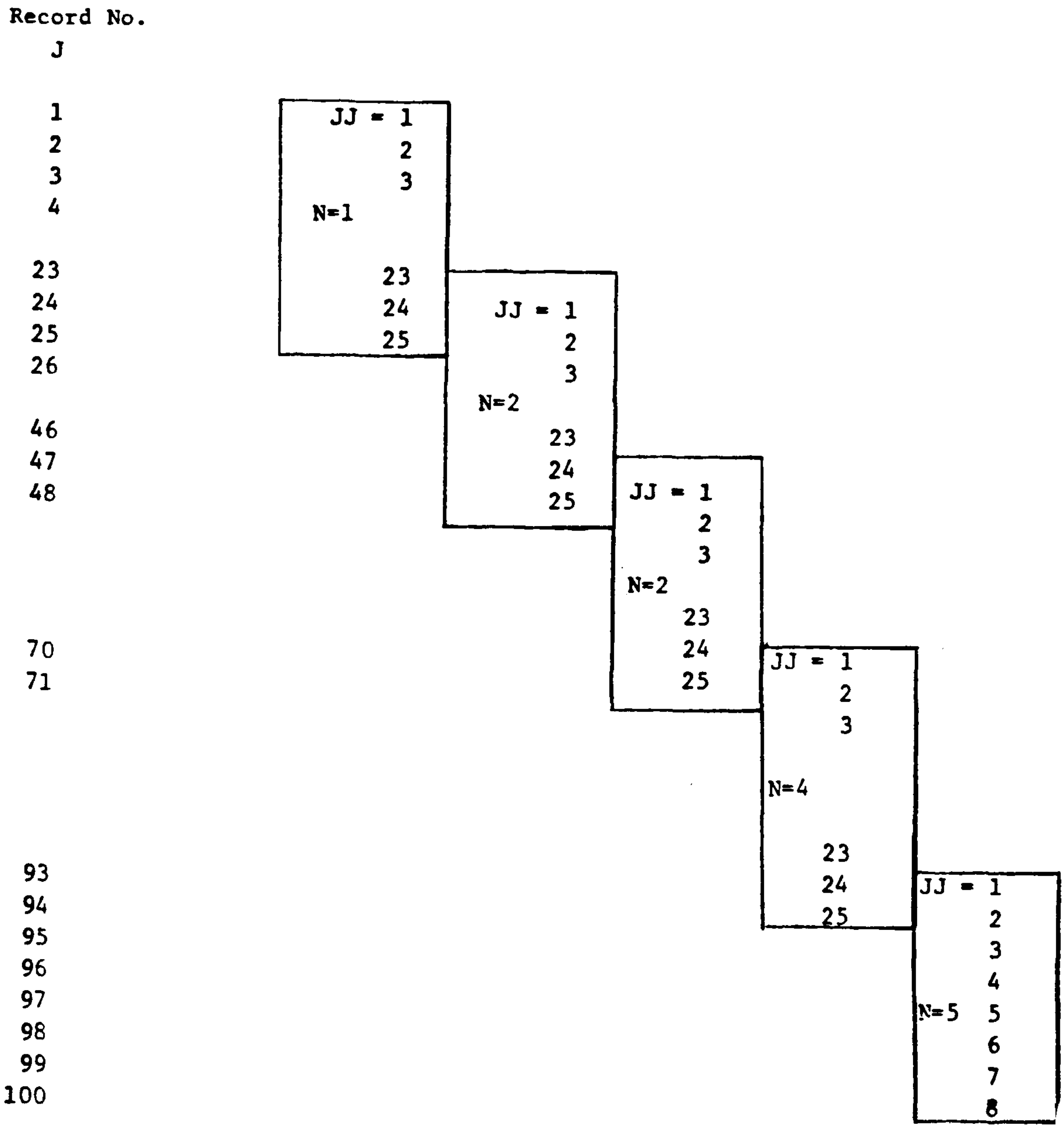
List of Symbols

JJ	,JJth station in core
NST	,No. records per block
NIST	,No. words per block
NPDRM = 24	,Unit number
P	,Stream function

Theory

The stream function array P(JJ,KK) is arranged in core as described in subroutine READPF, Fig. 12. When an iterative sweep of one block is complete, the new updated solution is written on a disk file. This occurs when JJ = NST-1.

FIG. 12 I/O for Streamline Curvature Solution
Overlapping Blocks



Subroutine WRTBLD

Object

Write output for WBLEED

Options

None

Variables

See subroutine WBLEED

Theory

This subroutine prints the output from subroutine WBLEED according to the output format described in Section 4.3.

Subroutine WRTCKI

Object

Write output for CKINPT

Options

None

Variables

See subroutine CKINPT

Theory

This subroutine prints the output from subroutine CKINPT according to the output format described in Section 4.3.

Subroutine WRTCAL

Object

Write output for CALINV

Options

None

Variables

See subroutine CALINV

Theory

This subroutine writes the output from subroutine CALINV according to the output format described in Section 4.3.

Subroutine WRTFØU

Object

Print solution on output data line

Options

None

Variables

CØMMØN BLØCK Variables

Theory

The dependent variables at the output data points are printed in three coordinate systems using the direction cosines given by

$$C_{ij} = \begin{pmatrix} COS\theta & -SIN\theta & 0 \\ SIN\theta & COS\theta & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{1}$$

where θ is the angle between the S coordinate and the z axis (R,Z) coordinates, or the angle between the S coordinate and the X axis (Y,X) coordinates.

Subroutine WRTGDC

Object

Write output summary - coordinate calculation

Options

None

List of Symbols

CØMMØN BLØCK variables

Theory

The output from GDUCT is printed on page 1 and the output from CØØRST is printed on page 2.

Subroutine WRTINP

Object

Write input parameters and variables

Options

The options are the same as the input read options

List of Symbols

Common block variables

Theory

The input data is printed as follows:

Page 1	Input parameters
Page 2	Inlet flow data
Page 3	Strut data
Page 4	Strut thickness distribution
Page 5	Strut flow variables

Subroutine WRTSØV

Object

Print solution at selected stations

Options

IØPT4	Print solution every IØPT4th station
IVTEST >	For separated flow print every station
IØPT4 <	Extended printout every IØTP4th station

List of Symbols

CØMMØN BLØCK variables

Theory

The dependent variables are printed according to the input print option IØTP4.

Subroutine WRTSUM

Object

Write output summary pages

Options

IØPT15	First calculated station
IØPT16	Last calculated station
JSTØ	Number of stations stored on F file

IØPT15 $\leq$ J $\leq$ IØPT16 Solution complete

IØPT15 $\leq$ J $\leq$ JSTØ + IØPT15-1 Solution not complete

Variables

CØMMØN BLØCK variables

Theory

This subroutine prints the mass flow weighted average flow, pressure and skin friction coefficient, and convective heat transfer data.

Function XH(J)

Object

Find distance on hub wall

Options

Evaluate at point J

List of Symbols

None

Theory

The distance along the hub wall is given by

$$XH = \left[R_H(J) - R_H(J-1)^2 + \Delta Z^2 \right]^{1/2} \tag{1}$$

Function XT(J)

Object

Find distance along tip wall

Options

Evaluate at point J

List of Symbols

None

Theory

The distance along the tip wall is given by

$$XT = \left\{ \left[R_T(J) - R_T(J-1) \right]^2 + \left[Z_T(J) - Z_T(J-1) \right]^2 \right\}^{1/2} \qquad (2)$$

Subroutine ZERØ (ADDR, NUM)

Object

Set real variables to zero

Options

None

List of Symbols

ADDR	Real array
NUM	Number of elements

Theory

This subroutine sets the first NUM real variables in array ADDR to zero.

8.0 LIST OF SYMBOLS

$A_k, B_k, C_k, D_k, E_k, F_k$	Coefficients used in matrix solver
A^+	Van Driest constant (26.0)
B	Constant used in coordinate stretching
C_f	Convection terms
C_f	Skin friction coefficient
C_p	Specific heat $(ft^2/sec^2/°R)$
C_1, C_2, C_3, C_μ	Empirical constants in Two Eq. Turbulence model
e	Rate of strain (units) (1/sec)
E	Dissipation Rate dimensionless $\frac{\rho_r}{\mu_r} \left(\frac{r_r}{u_r}\right)^2 \varepsilon$
$E_{ns}, E_{n\phi}$	Streamwise and tangential strain (dimensionless) $(e/(\rho_r u_r^2))$
F	Ratio mixing length to flat plate mixing length
$\bar{F}$	Ratio mixing length to wake mixing length
F_k	Coefficient in Poisson equation
g	Gap between walls (ft)
G	Gap between walls (dimensionless) (g/r_r)
h	Duct height (ft)
H	Height of duct (dimensionless) (h/r_r)
I	Turbulence Intensity $(\overline{u'u'}/\bar{u}^2)$
k	Turbulent kinetic energy $(ft/sec)^2$
K	Turbulent kinetic energy (dimensionless) (k/u_r^2)

K_c	Streamline curvature correction (dimensionless)
$_n$	Curvature of coordinate potential line (dimensionless) (r_r/r_n)
K_s	Curvature of coordinate streamline (dimensionless) (r_r/r_s)
K_ϕ	Curvature of the swirl flow (dimensionless) (r_r/r_ϕ)
K_∞	Freestream turbulent kinetic energy (dimensionless) $(\overline{u'u'}_\infty/u_r^2)$
ℓ	Mixing length (ft)
ℓ_o	Mixing length flat plate (ft)
M	Mach number
M_r	Reference Mach number
n	Normal coordinate (dimensionless)
p	Static pressure (psf abs)
p_r	Reference pressure (psf abs)
P_T	Turbulence production (dimensionless) $\left(\frac{r_r}{\rho_r u_r^3} P_p\right)$
P_r	Prandtl number (laminar) $(C_p\mu/\lambda)$
P_{r_T}	Prandtl number (turbulent) $(C_p\mu/\lambda)_T$
q	Heat flux (lb/ft/scc)
Q	Heat flux (dimensionless) $q/(\rho_r u_r C_p T_r)$
r_n	Curvature of coordinate potential line
r_r	Reference radius (ft)

LIST OF SYMBOLS (Cont'd)

r_s	Curvature of coordinate streamline
r	Curvature of the swirl flow
R	Radius, r/r_r (dimensionless)
R_{is} $\bar{R}_{is}$	Richardson numbers for streamwise curvature (dimensionless)
R_{it}	Turbulent Richardson number (dimensionless)
$R_{i\phi}$, $\bar{R}_{i\phi}$	Richardson numbers for swirl (dimensionless)
R_n	Radius of curvature of potential line (dimensionless)
R_s	Radius of curvature of streamline (dimensionless)
R_t	Turbulent Reynolds number
Re_r	Reference Reynolds number $(\rho_r u_r T_r/\mu_r)$
R	Gas constant $(ft^2/sec^2/°R)$
s	Streamwise coordinate (dimensionless)
S_E	Dimensionless source in dissipation equation $(r_r^3/(\mu_r u_r^3)(S_\varepsilon)$
S_k	Source Term in turbulenct kinetic energy equation (units)
S_K	Dimensionless source is turbulent kinetic energy Eq. $(r_r/\rho_r/u_r^3 S_k)$
S_ε	Source term in dissipation equation (units)
u_{max}	Magnitude of freestream velocity (ft/sec)
u_r	Reference velocity (ft/sec)
u_s, u_n, u_ϕ	Velocity components (ft/sec)

u^*	Friction velocity ($\sqrt{\tau_w/\rho_w}$ ft/sec)
$\overline{u'u'}, \overline{u'v'}$	Reynolds stress (ft^2/sec^2)
U	Magnitude of velocity (dimensionless) (u/u_r)
U_s, U_n, U_ϕ	Velocity components (dimensionless) (u/u_r)
$\bar{U}_s, \bar{U}_\phi$	Freestream velocity components (dimensionless) (u/u_r)
U^+	Universal velocity (u/u^*)
V	Metric scale coefficient (dimensionless)
y	Distance normal to wall (ft)
Y	Distance normal to wall (dimensionless) (y/r_r)
Y^+	Universal distance to wall ($\rho_w u^* y/\mu_w$)
z	Axial distance (ft)
Z	Axial distance (dimensionless) (z/r_r)
α	Swirl angle (deg)
α_s, α_ϕ	Empirical constants for Bradshaw mixing length correction
β_s, β_ϕ	Empirical constants for Eide-Johnston mixing length correction
γ	Ratio of specific heats (dimensionless)
Γ_k, Γ_e	Coefficients in two eq. turbulence model
δ^*	Displacement thickness (ft)
ΔK_s	Curvature of viscous flow streamlines relative to coordinates

ε	Turbulence dissipation (ft^2/sec^3)
θ	Angle of streamline to axis (deg)
Θ	Static temperature (T/T_r)
Θ_T	Total temperature (T_T/T_r)
η	Transform normal coordinate
I	Entropy dimensionless (I/R)
κ	von Karmon constant (.41)
λ	Thermal conductivity (lb/sec/deg R)
μ	Molecular viscosity (slug/ft/sec)
μ_E	Effective viscosity (slug/ft/sec)
μ_r	Reference viscosity (slug/ft/sec)
μ_T	Turbulent viscosity (slug/ft/sec)
ν	Iteration counter
Π	Static pressure (dimensionless) (p/p_r)
Π_T	Total pressure (dimensionless) (p_T/p_r)
ρ	Density ($slug/ft^3$)
ρ_r	Reference deposits ($slug/ft^3$)
ρ_w	Density, at wall ($slug/ft^3$)
P	Density (dimensionless (ρ/ρ_r)
σ_E,σ_K	Empirical constants in two eq. turbulence model
$\Sigma_{ns},\Sigma_{n\phi}$	Streamwise and tangential stress (dimensionless) ($\tau/\rho_r/u_r^2$)

LIST OF SYMBOLS (Cont'd)

τ	Shear stress (lb/ft^2)
χ	Clauser Constant (.0168)
X	Normal coordinate transform $\partial\eta/\partial n$
ψ	Stream function (ft^2/sec)
Ψ	Stream function (dimensionless)
ω	Relaxation factor
ω	Wilcox dissipation rate
$\omega_n, \omega_s, \omega_\phi$	Vorticity components (dimensionless)
Ω	Relaxation factor

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16. Abstract
This User's Manual contains a complete description of the computer codes known as the Axisymmetric Diffuser Duct (ADD) code. It includes a list of references which describe the formulation of the ADD code and comparisons of calculation with experimental flows. The input/output and general use of the code is described in the first volume. The second volume contains a detailed description of the code including the global structure of the code, list of FORTRAN variables, and descriptions of the subroutines. The third volume contains a detailed description of the CODUCT code which generates coordinate systems for arbitrary axisymmetric ducts.

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